VOL. 27, NO. 9 AUGUST 1953

BUREAU OF PUBLIC ROADS
RECEIVED
JUL 24 1953
LIBRARY
c4

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

PUBLISHED BY
THE BUREAU OF
PUBLIC ROADS,
U. S. DEPARTMENT
OF COMMERCE,
WASHINGTON

Bituminous-surfaced highway (U.S. 17) between Georgetown and Myrtle Beach, S. C.

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

Vol. 27, No. 9 *August 1953*

Published Bimonthly

Edgar A. Stromberg, *Editor*

BUREAU OF PUBLIC ROADS
Washington 25, D. C.

WESTERN HEADQUARTERS
870 Market St.
San Francisco 2, Calif.

DIVISION OFFICES

No. 1. 718 National Savings Bank Bldg., Albany 7, N. Y.
Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont.

No. 2. 707 Earles Bldg., Hagerstown, Md.
Delaware, District of Columbia, Maryland, Ohio, Pennsylvania, Virginia, and West Virginia.

No. 3. 50 Seventh St., N. E., Atlanta 5, Ga.
Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee.

No. 4. South Chicago Post Office, Chicago 17, Ill.
Illinois, Indiana, Kentucky, Michigan, and Wisconsin.

No. 5. Federal Office Bldg., Kansas City 6, Mo.
Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota.

No. 6. 502 U. S. Courthouse, Forth Worth 2, Tex.
Arkansas, Louisiana, Oklahoma, and Texas.

No. 7. 870 Market St., San Francisco 2, Calif.
Arizona, California, Nevada, and Hawaii.

No. 8. 753 Morgan Bldg., Portland 8, Oreg.
Idaho, Montana, Oregon, and Washington.

No. 9. Denver Federal Center, Bldg. 40, Denver 2, Colo.
Colorado, New Mexico, Utah, and Wyoming.

No. 10. Federal Bldg., Juneau, Alaska.
Alaska.

PUBLIC ROADS is sold by the Superintendent of Documents, Government Printing Office, Washington 25, D. C., at $1 per year (foreign subscription $1.25) or 20 cents per single copy. Free distribution is limited to public officials actually engaged in planning or constructing highways, and to instructors of highway engineering. There are no vacancies in the free list at present.
The printing of this publication has been approved by the Director of the Bureau of the Budget, January 5, 1952.

Contents of this publication may be reprinted. Mention of source is requested.

IN THIS ISSUE

Studies of the Hardening Properties of Asphaltic Materials 187

U. S. DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary

BUREAU OF PUBLIC ROADS
FRANCIS V. du PONT, Commissioner

Studies of the Hardening Properties of Asphaltic Materials

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by JARL T. PAULS,
Chief, Bituminous Section,
and J. YORK WELBORN,
Highway Physical Research Engineer

The rate and amount of hardening of asphaltic materials is an important factor in the service behavior and life of bituminous pavements.

This article describes several methods which can be used for evaluating the hardening properties of asphaltic materials. Two methods, the abrasion test and the weathering-strength test, were developed and used for evaluating the hardening properties of a large number of asphaltic materials. These methods of test are based upon the changes in the physical properties of standard sand-asphalt mixtures during exposure to heat and air. The thin-film oven test, developed by the Bureau of Public Roads some years ago, was also used to evaluate the hardening of these asphaltic materials. Comparisons of the results of the abrasion test, the weathering-strength test, and the thin-film oven test show that the rate and amount of hardening of asphaltic materials can be determined by any of these methods.

From this study it is concluded that:

1. Asphalts differ in their hardening properties, depending on the source of the crude petroleum and the methods used in their manufacture.

2. When subjected to weathering, cracked asphalts become hard and brittle more rapidly than do uncracked asphalts and also develop a higher degree of hardness and brittleness, the rate of hardening increasing with the degree of cracking.

3. Increase in hardness of the asphalt as indicated by decrease in penetration is accompanied by changes in other properties, such as increase in softening point and decrease in ductility.

4. Since the thin-film oven test produces changes in the asphalt comparable to those produced by the other test methods and since it is a more rapid and simpler test to make, it is more suitable for use as a specification test.

AMONG the many factors that may cause the failure of a bituminous pavement, the hardening properties of the bituminous material are highly important. A quantitative knowledge of the tendency of an asphalt to harden is one of the indispensable measures in predicting the service behavior of a bituminous pavement. Investigations have shown that pavement failures increase when the penetration of the asphalt drops to certain critical values, which vary somewhat depending upon such factors as climate, flexibility of base and subgrade, and traffic conditions.

The hardening of an asphalt, as shown by a drop in its penetration, is accompanied by changes in other properties of the material. The test characteristics affected include ductility, softening point, and the amount of material insoluble in selective solvents. Some of these properties often are altered to a greater degree than can be accounted for by the decrease in penetration alone. In this report the changes in the properties of the asphaltic materials are discussed mainly from the standpoint of the decrease in penetration induced by various weathering or exposure conditions. The discussion of other characteristics is secondary, although they may be of equal or greater importance.

Asphalt in thin films may harden very rapidly when subjected to high temperatures. In contrast to the normally slow rate of hardening of the binders that occurs in the finished pavement, the alteration in the test characteristics of asphalts that may occur under certain mixing and laying conditions may be striking. In fact, there are data that show that the loss in penetration occurring in the mixing and laying operation may be greater than the loss subsequently occurring in the pavement over a period of as much as 10 years after construction.

In the mixing operation, because of the relatively large mass of the granular materials, compared to the small mass of the asphalt, the temperatures of such materials at the time they are placed in the mixing box have a greater effect than does the temperature of the asphalt. Heating asphalts in a large mass, such as is done in storage tanks at the mixing plant, does not lower their penetration appreciably. It is only when the asphalt coats the hot stone particles as a thin film in the mixing box that the conditions most favorable to rapid hardening are obtained.

Present information indicates that aggregate temperatures lower than 300°F. at the time of mixing are not particularly damaging to the more normal asphalts. However, many asphalts are adversely affected at only slightly higher temperatures, with rapidly increasing loss in penetration occurring with increasingly higher temperatures. Even when precautions are taken to reduce the damage to the asphalts which occurs in the mixing operations, particularly by keeping the mixing temperature only as high as required to obtain a good coating of the stone particles, the amount of hardening of the asphalt occurring in the mixing and laying operations and in subsequent service may nevertheless differ widely for different asphalts, depending on the source of the crude petroleum from which the asphalt is produced and the methods used in its refining.

Conclusions

From the studies made, it may be concluded that:

1. This investigation substantiates the fact developed by previous investigations that the hardening of asphalts caused by weathering is evidenced by a decrease in penetration and ductility and an increase in softening point.

2. Asphalts differ in their hardening properties, depending on the source of the crude petroleum and on the method of refining.

3. When subjected to weathering, asphalts that have been severely cracked in manufacture harden and develop brittleness more rapidly and to a greater degree than those that are not cracked. The rate of hardening increases with the degree of cracking.

4. The following tests have been found to be useful for obtaining a measure of the resistance of asphalts to heat or weathering as evidenced by rapidity and degree of hardening:

Table 1.—Source of crude and method of refining asphalt cements

Identification and source of crude (or where used)	Method of refining
1. California	Reduction and steam.
2. Do	Do.
3. Do	Do.
4. Venezuela	Pipe still, vacuum.
5. Do	Do.
6. Do	Do.
7. Kansas	Shell still.
8. Do	Do.
9. Do	Do.
10. Do	Do. (highly cracked).
11. Kentucky	Dubbs cracking process (highly cracked).
12. Do	Do.
13. Wyoming	Fire and steam (slightly cracked).
14. Mexican (Panuco)	Steam, Trumble pipe still (slightly cracked).
15. Do	
16. Columbia	Pipe still, vacuum.
17. Venezuela	Air and steam (slightly cracked).
18. Do	Pipe still, vacuum.
19. Arkansas (Smackover)	Vacuum at low temperature.
20. Do	Vacuum, 89 mp. flux.
21. Kentucky and Illinois	Fire and steam, probably blown.
22. Trinidad Lake	Fluxed.
23. Bermudez Lake	Fluxed.
24. California (San Joaquin)	
25. Field sample, Rhode Island	
26. Field sample, Virginia	
27. Venezuela	
28. Kentucky or Illinois	
29. California	
30. Kansas	(Highly cracked).
31. Do	
32. Do	
33. Wyoming	
34. Kansas	
35. Kentucky or Illinois	
36. Field sample, Virginia	
37. California	
39. Field Sample, Rhode Island	
40. Venezuela	
41. Do	
42. Kansas	Pipe still, vacuum.
43. Do	Do.
44. Do	Do.
45. Ohio	
46. Venezuela	
47. Kentucky	

(a) The abrasion test, in which resistance to abrasion of a standard asphalt mixture is inversely proportional to the hardness of the asphalt.

(b) The weathering-strength test, in which increase in compressive strength of a standard asphaltic mixture is generally proportional to the hardness of the asphalt.

(c) The Shattuck test, in which the hardness characteristics of the asphalt in a standard mixture are determined after the mixture has been exposed to heat in a standard manner.

(d) Outdoor exposure, in which the hardness characteristics of the asphalt contained in a standard asphaltic mixture are determined after exposure of the mixture to natural weathering.

(e) The thin-film oven test, in which the hardness characteristics of the asphalt are determined after it has been exposed to heat in an oven.

5. With any of the above-mentioned methods of test the same degree of hardening can be obtained by varying the time or temperature of exposure.

6. Of the test methods enumerated above, the thin-film oven test is the most suitable for use as a specification test because it requires the least amount of time, because the hardening of the asphalt is measured directly (rather than indirectly as in the case of the abrasion test and weathering-strength test), and because the test does not require the extraction and recovery of the asphalt, as in the case of the Shattuck test and outdoor exposure tests, and thus eliminates any uncertainty regarding the effect of the recovery procedure on the characteristics of the weathered asphalt.

Tests of Hardening Properties

The standard test now used for determining the hardening properties of asphalts is the test for loss on heating and the penetration test on the residue. In this test, a 50-gram sample of asphalt is placed in a metal container of such dimensions that the sample has a surface area of about 3.7 square inches and a depth of about thirteen-sixteenths of an inch. The sample is heated in an oven at 325°F. for 5 hours, after which the percentage loss of material and the loss in penetration are determined. It is generally agreed that, because of the relatively large depth of the sample with correspondingly small surface area, the conditions of this test are not sufficiently severe to evaluate the relative hardening properties of asphalt.

Another test of loss on heating is the thin-film oven test,[1] which appears to be a very

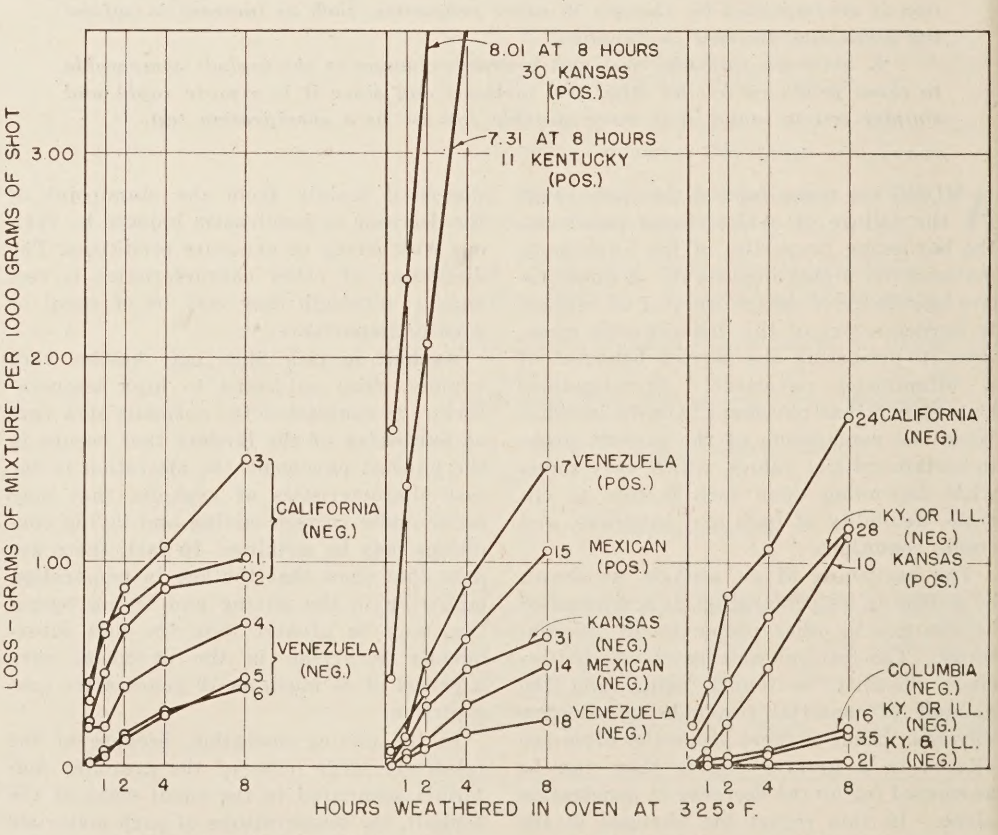


Figure 1.—Results of abrasion test on asphalt cements weathered at 325 °F.

---

[1] *The properties of the residues of 50-60 and 85-100 penetration asphalts from oven tests and exposure,* by R. H. Lewis and J. Y. Welborn. Public Roads, vol. 22, No. 2, April 1941. *Behavior of asphalts in thin-film oven test,* by R. H. Lewis and W. J. Halstead. Public Roads, vol. 24, No. 8, April-May-June 1946.

Table 2.—Results of abrasion test on asphalt cements after oven weathering at 325° F.

Identification and source of asphalt	Tests on the original asphalt			Abrasion loss[1] after oven-weathering at 325° F. for—					
	Oliensis spot test	Xylene equivalent.	Penetration at 77° F.	None	¼ hour	1 hour	2 hours	4 hours	8 hours
				Gms.	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*
1. California	Negative		54	3.34	0.32	0.68	0.76	0.91	1.02
2. Do	...do		90	1.86	.21	.45	.67	.87	.93
3. Do	...do		131	1.45	.41	.65	.87	1.07	1.50
4. Venezuela	...do		51	1.17	.18	.18	.38	.51	.70
5. Do	...do		88	.95	.01	.07	.13	.25	.43
6. Do	...do		138	.18	.01	.05	.15	.26	.39
7. Kansas	...do		61	1.36	.02	.04	.20	.40	.51
8. Do	...do		83					.25	.30
9. Do	...do		137	.05	.00		.02	.07	.20
10. Do	Positive	60–64	92	.99	.02	.08	.21	.49	1.14
11. Kentucky	...do	80–84	87	3.25	.43	1.37	2.07	5.54	7.31
12. Do	...do	80–84	102	2.75	.53	1.18	2.41	5.87	8.19
13. Wyoming	...do	20–24	95	1.50	.12	.27	.42	.73	1.27
14. Mexican	Negative		106	.19	.00	.05	.13	.31	.50
15. Do	Positive	24–28	101	1.38	.09	.19	.37	.63	1.06
16. Columbia	Negative		110	.17	.02	.04	.06	.08	.19
17. Venezuela	Positive	8–12	97	.77	.02	.14	.51	.90	1.47
18. Do	Negative		105	.05	.01	.04	.09	.17	.23
19. Arkansas	...do		96	.79	.11	.15	.20	.36	.55
20. Do	...do		98	.09	.00	.02	.03	.07	.18
21. Kentucky and Illinois	...do.[2]		105	.15	.00	.01	.02	.01	.03
22. Trinidad Lake			100	.83	.25	.56	.81	1.05	1.18
23. Bermudez Lake			102	.41		.27	.29	.51	85
24. California	Negative		89	2.40	.21	.51	.84	1.07	1.71
25. Field sample, Rhode Island	...do		65	1.40	.03	.13	.16	.28	.56
26. Field sample, Virginia	...do		89	.37	.02	.07	.16	.28	.33
27. Venezuela	...do		64	.63	.01	.04	.10	.35	.76
28. Kentucky or Illinois	...do		93	1.06	.12	.26	.42	.74	1.17
29. California	...do		102	2.01	.15	.36	.70	.86	.92
30. Kansas	Positive	88+	75	3.93	1.65	2.38	3.57	4.92	8.01
31. Do	Negative		75	.61	.08	.13	.30	.48	.64
32. Do	...do		76	1.32	.46	.49	.67	.97	1.36
33. Wyoming	...do		85	1.07	.23	.49	.62	.77	1.13
34. Kansas	...do		87	1.01	.03	.10	.31	.33	.66
35. Kentucky or Illinois	...do			.19	.01	.02	.03	.07	.17
36. Field sample, Virginia	...do		67	.59	.18	.25	.86	1.11	1.66
37. California	...do		100	1.91	.23	.65	.81	1.03	1.34
39. Field sample, Rhode Island	...do		67						
40. Venezuela	...do		86	1.24	.08	.38	.53	.75	.96
41. Do	...do		67	1.61	.61	.34	.57	.80	1.14
42. Kansas	...do		68	.35	.05	.05	.08	.23	.32
43. Do	...do		90	1.02	.49	.27	.46	.59	.90
44. Do	...do		132	.33	.07	.03	.09	.21	.48
45. Ohio	...do		94	.23	.03	.02	.03	.16	.57
46. Venezuela	...do		54	1.53	.28	.25	.24	.38	.96
47. Kentucky	...do		89	1.45	.50	.30	.28	.38	.62

[1] Loss in grams of mixture per 1,000 grams of shot. [2] Probably blown.

satisfactory method for evaluating the hardening properties of asphalts. In this test a 50-milliliter (approximately 50 gram) sample is placed in a tin 5.5 inches in diameter. Thus, its surface area is nearly 24 square inches and its depth is approximately one-eighth inch. As in the standard test, the sample is heated in an oven at 325°F. for 5 hours, after which the penetration, softening point, and ductility are determined.

Some investigators have preferred to study the effect of heat on asphaltic materials by subjecting aggregate mixtures containing these asphalts to some type of heat test, and then testing either the mixture by some physical test or the extracted and recovered asphalt for penetration, ductility, and softening point.

Two types of tests, both based on the changes occurring in the physical properties of standard mixtures after exposure to heat and air, were developed and used for this study. These were the abrasion test, which is similar to that developed by H. N. Hveem,[2] and the weathering-strength test.

The Abrasion Test

The abrasion test,[3] as made by the Bureau of Public Roads laboratory, was originally

---

[2] *Abrasion test,* by H. N. Hveem. California Highway and Public Works, Nov.-Dec. 1946.

[3] *Evaluation of asphalts by means of an abrasion test,* by J. T. Pauls and R. A. Peck. Proceedings of the Association of Asphalt Paving Technologists, vol. 19, 1950.

Table 3.—Results of abrasion test on liquid asphalts after oven weathering at 325° F.

Identification and source of asphaltic material	Tests on the distillation residue				Abrasion loss[1] after oven-weathering at 325° F. for—					
	Spot test	Penetration at 77° F.	Ductility at 77° F.	Softening point	None	¼ hour	1 hour	2 hours	4 hours	8 hours
		Cm.	*Cm.*	*° F.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*	*Gms.*
L-1. Kansas, RC-4	Negative	78	170	123	4.76	0.36	1.17	1.42	1.81	2.32
L-2. Do	.....do	82	130	124	3.07	.59	.73	1.31	1.59	1.96
L-3. Do	Positive[2]	95	132	114	9.03	.32	2.11	3.55	4.80	6.26
L-4. Kansas, MC-4	Negative	196	90	124	2.12	.10	.13	.21	.46	1.02
L-5. Do	.....do	246	70	126	.33	.01	.03	.10	.18	.36
L-6. Do	Positive[2]	158	80	126	2.46	.11	1.05	2.40	3.82	6.12
L-7. Michigan, SC-4	Negative					.00	.02	.05	.14	.68
L-8. Do	Positive[2]					.37	3.19	11.30	23.95	34.25

[1] Loss in grams of mixture per 1,000 grams of shot. [2] Highly cracked.

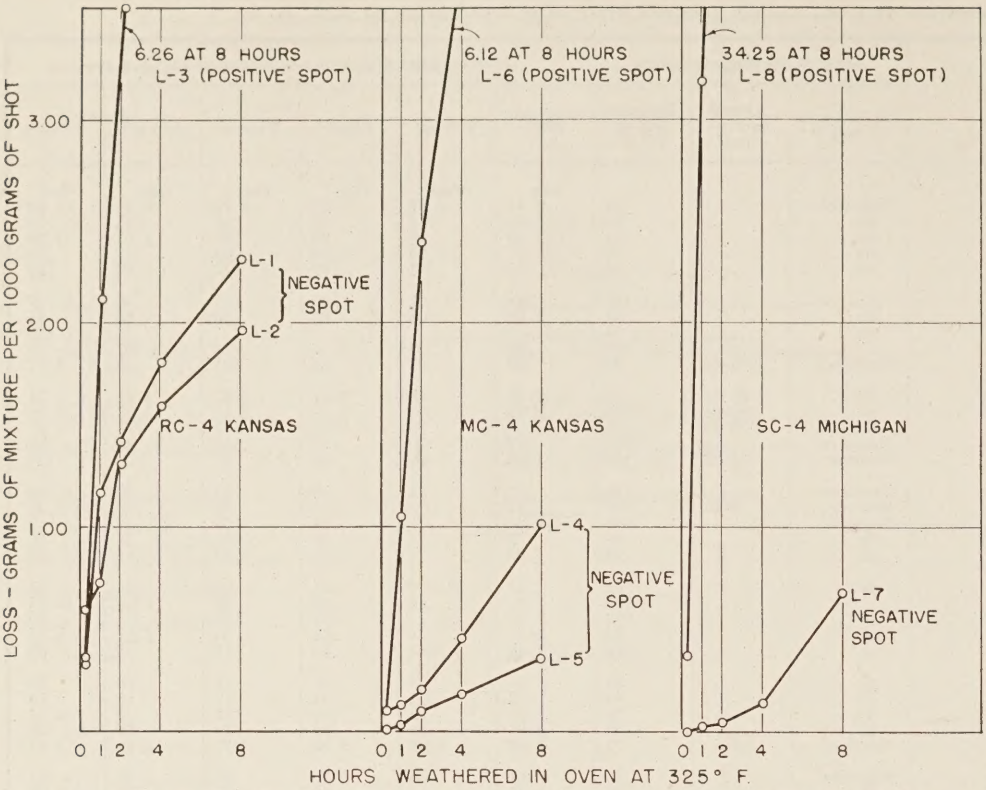


Figure 2.—Results of abrasion test on liquid asphalts weathered at 325°F.

described in a paper presented at the meeting of the Association of Asphalt Paving Technologists at St. Louis in 1950. The present paper includes the data from the original paper and also the results of additional work done subsequent to that time.

Essentially, the abrasion test consists of the determination of the loss in weight of an asphaltic mixture resulting from dropping a definite quantity of shot from a height of 1 meter onto the revolving horizontal surface of the weathered test specimen. It is assumed that the amount of loss, from the abrasive action of the shot, is directly related to the hardness of the asphalt.

In the California procedure developed by Hveem, molded mixtures of Ottawa sand and asphalt are weathered in a special weathering machine which employs an air temperature of 140°F. and direct rays of standard drying lamps, which emit the bulk of their energy in the infrared band. One cycle requires 5 hours of exposure and the complete test consists of nine cycles. In the Public Roads procedure, the test specimens are weathered in an oven at 325°F. for various periods of time from 15 minutes to 8 hours.

The important difference between the Public Roads test and the California test is in the weathering of the specimens. Oven weathering at 325°F., the procedure used in this study, is more rapid and if, as is believed, it evaluates the hardening properties of the materials properly, it has this advantage over the less severe and more time-consuming procedure used by Hveem.

Another difference in procedure is in the temperature at which the specimen is held while being tested. In the Public Roads laboratory the test is made at 77°F., whereas California uses 60°F. One would expect somewhat higher abrasion losses with the lower test temperature, other test conditions being the same. Exact control of the test temperature is most important in making this test because any change or difference in temperature quickly affects the consistency of the asphalt film on the surface of the sand particles and, consequently, the abrasion loss.

Abrasion losses were determined for oven-weathering periods ranging from 15 minutes to 8 hours, and for longer periods in a few instances. Weathering at a temperature of 325°F. for periods longer than 8 hours appeared to have no particular value although, as would be expected, the abrasion loss increased with an increase in the duration of the oven exposure.

Uniform oven weathering of the test specimens was not obtained in the early test work. Using a forced-draft type oven, the degree of weathering was found to differ considerably depending on the position of the individual test specimen in the oven. This variation in weathering was largely eliminated by placing the test specimens in an oven pan slightly deeper than the

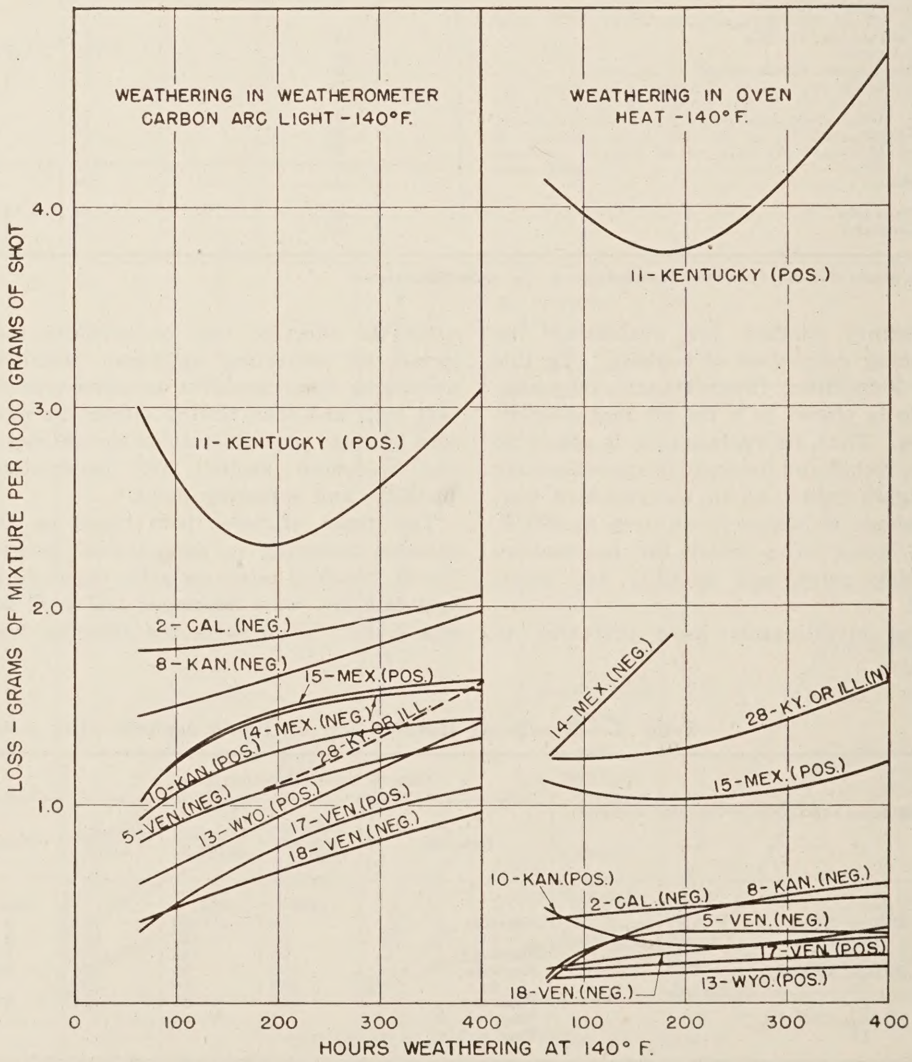


Figure 3.—Results of abrasion test on asphalt cements weathered at 140° F.

Table 4.—Comparative abrasion losses of asphalt cements after weathering at low temperature in oven and in weatherometer at 140° F.

Identification and source of asphalt	Abrasion loss[1] after weathering at 140° F. for—					
	64 hours		192 hours		400 hours	
	Weather-ometer	Oven	Weather-ometer	Oven	Weather-ometer	Oven
2. California	1.79	0.43	1.85	0.48	2.07	0.54
5. Venezuela	.82	.14	1.09	.36	1.33	.36
8. Kansas	1.45	.11	1.63	.44	1.99	.61
10. Kansas (highly cracked)	.94	.49	1.29	.30	1.43	.39
11. Kentucky (highly cracked)	3.00	4.14	2.31	3.78	3.10	4.79
13. Wyoming (slightly cracked)	.62	.13	.93	.16	1.43	.19
14. Mexican	1.01	1.24	1.46	1.86	1.58	....
15. Mexican (slightly cracked)	1.01	1.13	1.48	1.03	1.63	1.22
17. Venezuela (slightly cracked)	.37	.17	.77	18	1.09	.25
18. Venezuela	.42	.18	.66	24	97	.34
28. Kentucky or Illinois	.85	1.24	1.11	1.28	1.62	1.62

[1] Loss in grams of mixture per 1,000 grams of shot.

height of the specimens and covering the pan with a fine wire screen, thus reducing the air currents around the specimens. Very uniform weathering conditions were obtained by following this procedure.

In order to make a direct comparison between the result of slow and rapid weathering, two limited series of tests were made in which the weathering temperature was 140°F. One of these utilized a conventional weatherometer with carbon-arc lamps and controlled ventilators for maintaining the desired temperature, and the other series was weathered in an electric oven set to maintain a temperature of 140°F. The results of these comparative tests are included in this report. The details of the abrasion test are described on page 199.

The Weathering-Strength Test

The weathering-strength test developed and used in this study is based on the findings of previous investigations that the compressive strength on cylindrical specimens of bituminous mixtures, composed of Ottawa sand and asphalt, when tested in compression without lateral support, is primarily a measure of the cohesive strength of the asphalt, a property closely related to its penetration or hardness. Accordingly, the test procedure consists of exposing molded cylindrical specimens of Ottawa sand and asphalt mixtures in an oven at 325°F. for various periods of time and determining their compressive strengths.

The difficulty of weathering molded cylindrical specimens of asphaltic mixtures at a temperature of 325°F. without having them deform was overcome by placing the test specimens in perforated oversize cans and filling the space between the specimen and the can with Ottawa sand. The support provided by the sand prevented the test specimens from deforming in all instances, even when weathering mixtures of low strength such as those composed of liquid asphalts. The details of the weathering-strength tests are given on page 201.

A considerable number of asphaltic materials were tested by the abrasion test and by the weathering-strength test in this study. They cover a range in type, grade, source, and method of refining. The source and method of refining are not known for a number of these materials and, in some instances, the only identification available is the location in which they were used. Table 1 lists the asphalt cements which were tested, with such information relative to the source of the crude and the method of refining as is available.

Abrasion Test on Asphalt Cements

Test results on the original asphalt cements and the results of the abrasion test are given in table 2.

Generally low abrasion losses were obtained on all the negative-spot asphalts prepared from the midcontinent petroleums. Of the materials from this source, No. 21, made from Kentucky-Illinois petroleum and reported as probably blown, had the lowest loss in abrasion, 0.03 grams, after 8 hours of oven weathering. More typical abrasion losses on materials from this field were those obtained from Arkansas No. 20, Kansas No. 31, and Kentucky or Illinois No. 35. They were 0.18, 0.64 and 0.17 grams, respectively. The highest losses for the negative-spot materials from the midcontinent petroleum area were 1.17 for Kentucky or Illinois No. 28, and 1.36 for Kansas No. 32.

Very high losses were obtained on the highly cracked midcontinent materials Nos. 11 and 12 from Kentucky, and No. 30 from Kansas. The loss on No. 11 after 8 hours of weathering was at the rate of 7.31 grams, on No. 12, 8.19 grams, and on No. 30, 8.01

Table 5.—Weathering-strength test results on asphalt cements

Identification and source of asphalt	Tests on original asphalt		Compressive strength at 77° F. after weathering for—					
	Oliensis spot test	Penetration at 77° F.	1 hour	2 hours	3 hours	4 hours	6 hours	8 hours
			P.s.i.	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*
1. California	Negative	54	72	136	199	264	323	351
2. Do	do	90	41	84	....	208	....	352
3. Do	do	131	24	53	129	176	222	257
4. Venezuela	do	51	63	107	....	169	....	209
5. Do	do	88	34	54	....	118	....	191
6. Do	do	138	21	37	58	89	123	145
7. Kansas	do	61	62	88	115	129	142	144
8. Do	do	83	40	69	....	103	....	117
9. Do	do	137	19	37	49	76	100	111
10. Do	Positive	92	14	18	20	21	22	29
11. Kentucky	do	87	115	111	45	46	50	47
12. Do	do	102	115	111	45	45	....	46
13. Wyoming	do	95	33	63	....	108	....	116
14. Mexican	Negative	106	33	60	....	120	....	180
15. Do	Positive	101	31	64	....	93	....	131
16. Columbia	Negative	110	21	43	....	105	....	162
17. Venezuela	Positive	97	49	73	110	122	....	146
18. Do	Negative	105	29	48	78	98	....	156
19. Arkansas	do	96	18	33	50	63	96	119
20. Do	do	98	18	30	48	55	89	97
21. Kentucky and Illinois[1]	do	105	14	25	....	44	....	62
22. Trinidad Lake	....	100	41	51	89	132	151	191
23. Bermudez Lake	....	102	47	65	....	170	190	210
24. California	Negative	89	46	94	169	241	290	319
25. Field sample, Rhode Island	do	65	32	59	87	112	146	191
26. Field sample, Virginia	do	89	25	42	62	90	132	158
27. Venezuela	do	64	60	86	118	135	152	174
28. Kentucky and Illinois	do	93	38	72	....	115	....	138
29. California	do	102	31	100	....	189	....	342
30. Kansas	Positive	75	128	118	....	92	....	102
31. Do	Negative	75	43	74	....	104	....	132
32. Do	do	76	29	59	....	116	....	149
33. Wyoming	do	85	27	48	....	122	....	144
34. Kansas	do	87	29	54	....	95	....	132
35. Kentucky or Illinois	do	89	26	44	....	75	....	123
36. Field sample, Virginia	do	67	47	89	....	169	....	250
37. California	do	100	20	54	....	158	....	284
39. Field sample, Rhode Island	do	67	29	63	....	152	....	237
40. Venezuela	do	86	36	66	....	118	....	169
41. Do	do	67	24	36	....	74	....	138
42. Kansas	do	68	39	65	....	106	....	154
43. Do	do	90	16	23	....	55	....	117
44. Do	do	132	15	28	....	58	....	100
45. Ohio	do	94	18	36	....	68	....	101
46. Venezuela	do	54	44	65	....	108	....	177
47. Kentucky	do	89	19	32	....	58	....	115

[1] Probably blown.

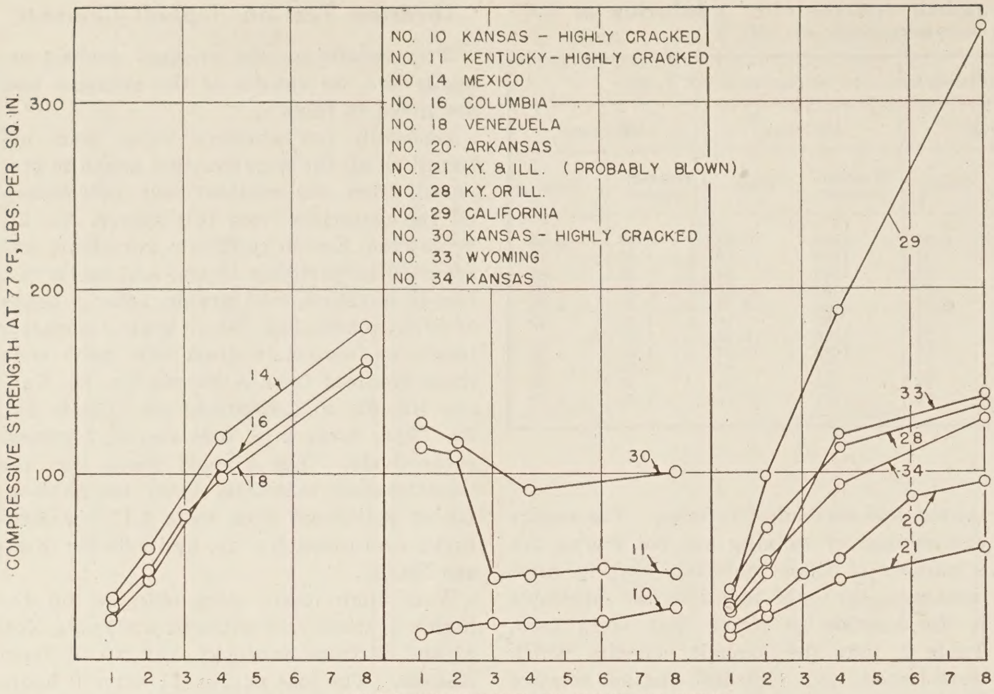
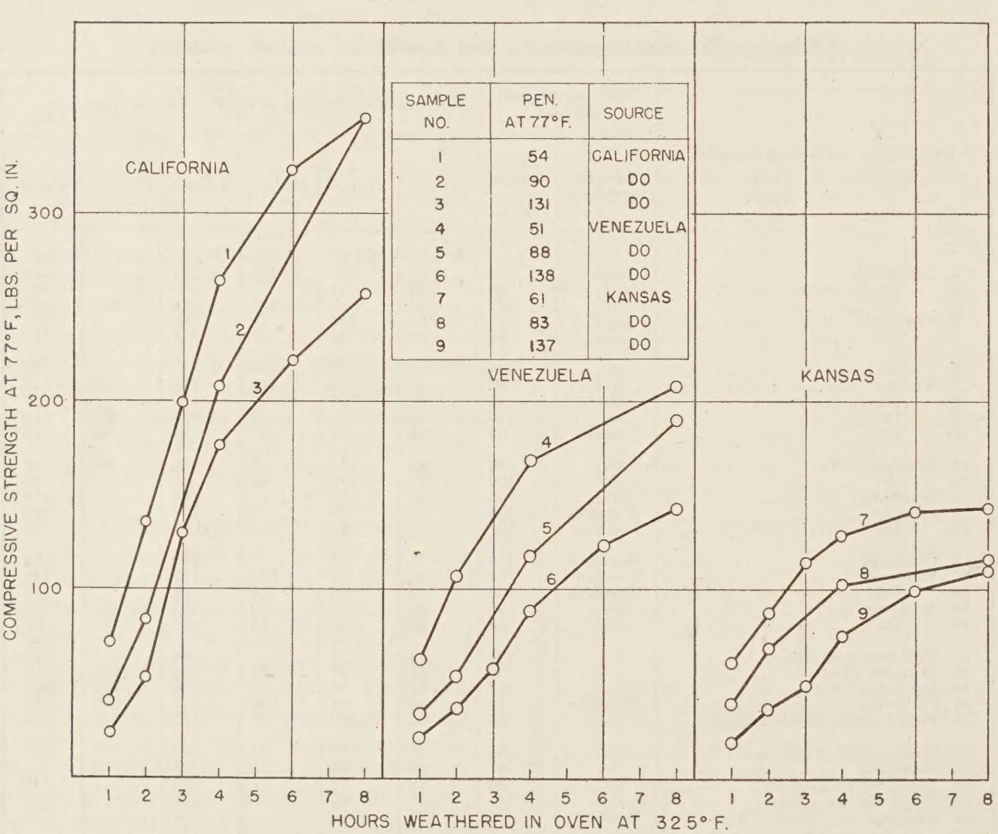


Figure 4.—Weathering-compressive strength test results, asphalt cements.



SAMPLE NO.	PEN. AT 77°F.	SOURCE
1	54	CALIFORNIA
2	90	DO
3	131	DO
4	51	VENEZUELA
5	88	DO
6	138	DO
7	61	KANSAS
8	83	DO
9	137	DO

Figure 5.—Results of weathering-compressive strength test showing effect of source of crude and the penetration of the original asphalt.

grams. The loss on the highly cracked material, No. 30, may be compared with the loss of only 0.64 grams on No. 31, a negative-spot material from the same source. The loss on Nos. 11 and 12 may be compared with the loss of only 0.17 on No. 35, and a loss of 0.62 on No. 47, negative-spot materials from a similar crude.

From sources other than midcontinent fields the results are not so consistent. The Trinidad and Bermudez asphalts and the negative-spot California asphalts had comparatively high abrasion losses, while some of the other negative-spot foreign and domestic asphalts had relatively low losses. The two slightly cracked materials, showing positive spots—No. 15 from Mexico and No. 17 from Venezuela—had high abrasion losses as compared with the negative-spot materials No. 14 and No. 18 from the same respective crude oils. Typical differences between negative- and positive-spot materials are shown in figure 1.

There is some indication that, in general, the abrasion losses are somewhat higher for the more viscous grades of asphalts from a given crude than for the softer materials. This is shown by the abrasion losses obtained on the Venezuela materials Nos. 4, 5, and 6, and the Kansas materials Nos. 7, 8, and 9. In the California group, materials Nos. 1, 2, and 3, the No. 3 asphalt, the least viscous of the three, does not conform to this general relation as the abrasion loss for this material is somewhat higher than that for the more viscous materials, Nos. 1 and 2, from the same source.

Abrasion Test on Liquid Asphaltic Materials

The results of abrasion tests on a limited number of liquid asphaltic materials are given in table 3. The same relation between positive- and negative-spot materials with respect to abrasion loss was obtained with cutbacks and slow-curing asphaltic materials as was found in the results of tests on the paving asphalts. A positive-spot *RC*–4 cutback (No. L–3) made from a Kansas crude had a loss of 6.26 grams after 8 hours of weathering compared with losses of 2.32 and 1.96 grams on two negative-spot *RC*–4 materials (Nos. L–1 and L–2) from the same source. In the case of *MC*–4 materials from Kansas, the positive-spot material No. L–6 had a loss of 6.12 grams while the negative-spot materials, Nos. L–4 and L–5, had losses of only 1.02 and 0.36 grams, respectively. No. L–7, a negative-spot *SC*–4 material from Michigan, had a loss of only 0.68 grams whereas No. L–8, a positive-spot *SC*–4 material from the same source, had a loss of 34.25 grams. These relations are shown graphically in figure 2.

Losses from Slow Weathering

As stated before, some work has been done to correlate the abrasion losses from mixtures weathered rapidly at 325°F., with those from mixtures weathered slowly at 140°F. Two different methods were used in the slow-weathering study: (1) Conventional weatherometer with carbon-arc lamps, a rotating shelf, and an air-control system to maintain the interior temperature at 140°F.; and (2) an electric oven with mechanical convection and temperature control.

The abrasion losses resulting from weathering in the oven at 140°F. and those resulting from exposure in the weatherometer are given in table 4 and plotted in figure 3. These comparative tests were made on 11 materials. Weathering periods of 64, 192, and 400 hours were used.

In general, higher abrasion losses resulted from weathering in the weatherometer than from weathering in the oven at 140°F. No. 11, a severely cracked material, was an exception in that oven weathering at 140°F. caused very much higher abrasion loss than did weathering in the weatherometer. Also, in the case of No. 14, a negative-spot material from Mexico, somewhat higher loss occurred in the oven than in the weatherometer after 192 hours of exposure. In the case of material No. 28, oven weathering produced a higher loss than did the weatherometer at 64 hours and 192 hours, but the losses by the two methods of weathering were the same at 400 hours of weathering.

Less satisfactory differentiation between cracked and uncracked materials was obtained by weathering at 140°F. in the weatherometer than by weathering in the oven at 325°F. For the positive-spot material No. 17 and the negative-spot material No. 18, both from the same source, the losses in abrasion for oven weathering at 325°F. for 8 hours were 1.47 and 0.23 grams, respectively (see table 2); while for weathering in the weatherometer for 400 hours, the losses were 1.09 and 0.97 grams (table 4).

Weathering in this particular type of weatherometer results in a rapid surface-hardening effect on the test specimens with very slow hardening below the immediate surface. The rate of abrasion loss at the immediate surface would therefore probably be very high, while the rate of loss from the mixture below the surface would be comparatively low.

Slow weathering in the oven at 140°F., up to 400 hours, also failed to differentiate satisfactorily between the cracked and non-cracked materials. Only in the case of No. 11, a very highly cracked material, is this property of the material definitely shown. With the Venezuelan asphalts, the positive-spot material No. 17 showed a lower loss (0.25 grams) after 400 hours in the 140°F. oven than did the negative-spot material No. 18, (0.34 grams) after the same exposure. Indications are that weathering in the low temperature oven is not severe enough to bring out differences in the hardening properties of the asphalts within a reasonable period of weathering.

The following is a summary of the abrasion test results as discussed above:

1. In general, comparatively low abrasion losses were obtained on the negative-spot asphalts prepared from the midcontinent petroleums.

2. Of the negative-spot domestic asphalts included in this investigation, the California materials gave, in general, the higher abrasion losses.

3. The positive-spot asphalts were found to have high abrasion losses compared to the non-cracked materials from the same source. Generally, the amount of loss varied directly with the degree of cracking.

4. On the basis of results of the abrasion test, a direct comparison of materials from different sources is not warranted, as the abrasion loss of a negative-spot material from one source may be higher than that of a positive-spot material from a different source. On the other hand, the abrasion test appears to indicate quite accurately differences in quality that are due to various manufacturing procedures where comparisons are between materials from the same source.

5. The results of the abrasion test made with specimens weathered in an oven at 325°F. are more informative than when the specimens are weathered in an oven or in a weatherometer at 140°F.

The Weathering-Strength Test

Compressive strengths of the weathered specimens are given in table 5. The effect of time of weathering at 325°F. on the compressive strength of the molded specimens is shown in figures 4 and 5. Table 6 and figure 6 give similar data for the liquid asphaltic materials included in this study.

The compressive strength of the test specimens, except those containing highly cracked asphalt, increased with increased time of weathering up to 8 hours, the longest period of weathering used. The test specimens containing the highly cracked asphalts, Nos. 11, 12, and 30, decreased in strength after the first hour of weathering until, after weathering for 3 or 4 hours, they reached a substantially constant strength. The only other highly cracked asphalt cement tested, No. 10 from Kansas, differed from these in that it gave considerably lower strength results and showed some slight increase in strength with increased weathering. Mixtures containing the asphalts that showed positive spots but were only slightly cracked, Nos. 13, 15, and 17, showed increase in strength with increased exposure. No. 20, an uncracked asphalt from Arkansas, showed a relatively low increase in strength with weathering as did No. 21 from Kentucky and Illinois, a material reported as probably blown.

For the uncracked materials, the source of the crude from which the asphalt was obtained is shown to have a major effect on the rate of increase in strength on weathering of the mixture. The California

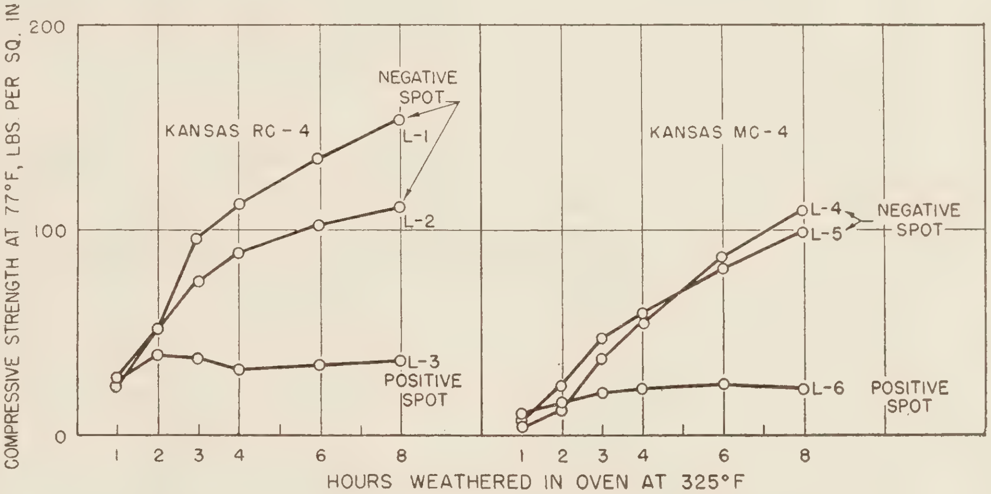


Figure 6.—Weathering-strength test results, cutback asphalts.

Table 6.—Results of weathering-strength test on cutback asphalts

Identification and source of asphaltic material	Tests on the distillation residue							Compressive strength at 77° F. after weathering for—					
	Oliensis spot test	Penetration at 77° F.	Ductility at 77° F.	Softening point	Residue from thin-film oven test			1 hour	2 hours	3 hours	4 hours	6 hours	8 hours
					Penetration at 77° F.	Ductility at 77° F.	Softening point						
			Cm.	° F.		Cm.	° F.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
L-1. Kansas, RC-4	Negative	78	170	123	46	90	137	23	51	95	112	135	154
L-2. Do	do	82	130	124	46	15	144	26	51	75	89	102	111
L-3. Do	Positive [1]	95	132	114	33	42	134	27	39	37	32	34	36
L-4. Kansas, MC-4	Negative	196	90	124	74	164	124	3	13	36	55	86	109
L-5. Do	do	246	70	126	90	81	126	7	24	47	59	81	99
L-6. Do	Positive [1]	158	80	126	51	99	126	10	15	20	22	24	22

[1] Highly cracked.

Table 7.—Tests on asphalt recovered from oven-weathered cylinders,[1] and abrasion and compressive-strength tests of molded specimens

Identification and source of asphalt (and original penetration)	Time of weathering	Tests on asphalt recovered from weathered cylinders			Tests on molded specimens after oven-weathering at 325° F.	
		Penetration at 77° F.	Ductility at 77° F.	Softening point	Abrasion loss	Compressive strength at 77° F.
	Hours		*Cm.*	*°F.*	*Grams*	*Lbs./sq. in.*
2. California (90 pen.)	1	40	250+	138	0.45	41
	2	19	93	151	.67	84
	4	10	5	184	.87	208
	8	4	0	228	.93	352
5. Venezuela (88 pen.)	1	39	37	141	.07	34
	2	25	7	162	.13	54
	4	17	3	192	.25	118
	8	11	2	250	.43	191
8. Kansas (83 pen.)	1	36	7	152	....	40
	2	26	4	180	....	69
	4	20	3	212	.25	103
	8	14	1	267	.30	117
14. Mexican (106 pen.)	1	39	23	148	.05	33
	2	29	8	165	.13	60
	4	20	4	187	.31	120
	8	11	0	260	.50	180
15. Mexican (101 pen.)	1	34	5	160	.19	31
	2	24	3	189	.37	64
	4	16	2	249	.63	93
	8	9	1	325	1.06	131
21. Kentucky and Illinois (105 pen.)	1	70	37	132	.01	14
	2	58	14	140	.02	25
	4	40	5	160	.01	44
	8	31	3	190	.03	62
28. Kentucky or Illinois (93 pen.)	1	39	48	139	.26	38
	2	23	6	159	.42	72
	4	17	4	179	.74	115
	8	....	....	....	1.17	138
29. California (102 pen.)	1	33	140	133	.36	31
	2	17	17	151	.70	100
	4	10	4	178	.86	189
30. Kansas (75 pen.) (highly cracked)	1	12	5	160	2.38	128
	2	8	1	190	3.57	118
	4	4	0	251	4.92	92
31. Kansas (75 pen.)	1	32	5	160	.13	43
	2	23	3	186	.30	74
	4	17	2	217	.48	104
32. Kansas (76 pen.)	1	43	18	140	.49	29
	2	29	5	160	.67	59
	4	21	3	185	.97	116
33. Wyoming (85 pen.)	1	37	16	141	.49	27
	2	27	6	155	.62	48
	4	18	3	184	.77	122
34. Kansas (87 pen.)	1	40	10	146	.10	29
	2	28	4	165	.31	54
	4	21	3	191	.33	95

[1] 2- by 2-inch molded cylinders oven-weathered at 325° F.

asphalts, Nos. 1, 2, 3, 24, 29, and 37, had the highest rate of increase in strength during weathering and the highest strength after 8 hours of weathering. The asphalts from some of the midcontinent fields gave comparatively low strength values after 8 hours, while the foreign materials gave strength values between those of the midcontinent and California asphalts.

The strength curves differ with differences in penetration of the original asphalt. In general, the more viscous materials from a given source gave somewhat higher strengths after weathering than did the less viscous ones. This is illustrated in figure 5 where the strength of the groups of California, Venezuela, and Kansas asphalts each show increased strength with decreasing penetration.

In table 6 and figure 6 are shown the weathering-strength test results on mixtures containing cutback asphalts *MC*–4 and *RC*–4. Very low weathering-strength curves were obtained for the highly cracked materials L–3 and L–6 as compared to the uncracked materials.

The following is a summary of the weathering-strength test results as discussed above:

1. Mixtures containing uncracked asphalts increased in strength for increasing periods of oven weathering up to 8 hours, the maximum period of weathering used in this investigation.

2. There was a wide difference in the rate of increase of strength and in the strength after 8 hours of oven weathering for asphalts from the various sources.

3. Three mixtures containing cracked asphalts attained relatively high strength in the early weathering periods and then decreased in strength as the weathering period was increased to 3 or 4 hours. A fourth cracked asphalt with a somewhat lower zylene equivalent (Kansas No. 10) had a low strength after 1 hour of weathering and thereafter showed only slight increase in strength for longer periods of weathering.

It has been shown that the abrasion loss and the strength of molded Ottawa sand and asphalt mixtures, when weathered for various periods of time, differ widely depending on the source of the asphalt and the method used in its manufacture. In order to determine if this difference in abrasion loss and strength is a measure of the difference in hardness of the contained asphalts, the following study was made.

Tests on Recovered Asphalts

In order to determine the changes in the characteristics of the asphalts after various periods of weathering, a number of the asphalts included in this study were extracted and recovered from test specimens weathered by the same method used in the compressive-strength test. To do this, a number of specimens were made for each weathering period to allow extraction and recovery of a sufficient amount of the asphalt to permit determining the penetration, ductility, and softening point of the materials at the various weathering periods. The Abson test method was used in recovering the asphalt. The results of tests on the recovered asphalts are given in table 7, together with the results of the abrasion and compressive-strength tests for the same periods of weathering.

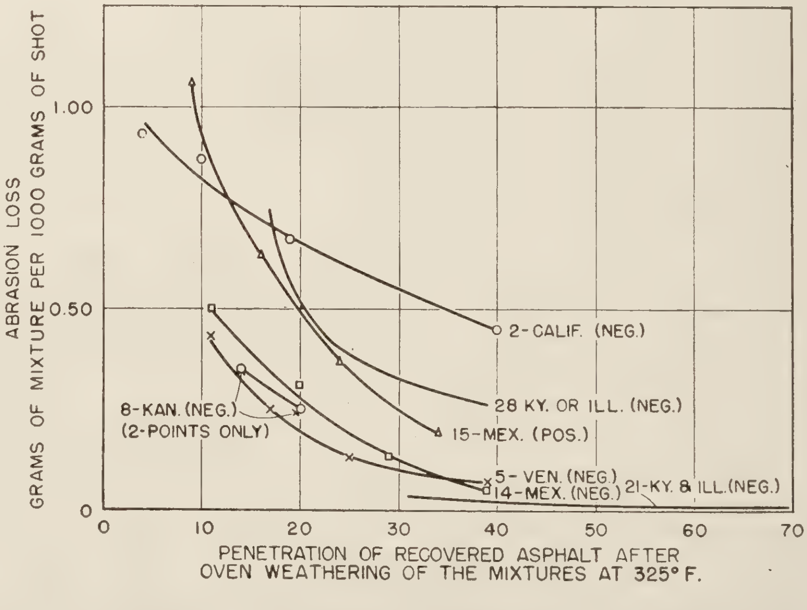


Figure 7.—Relation of the loss in the abrasion test to the penetration of the asphalts recovered from oven-weathered, 2 by 2-inch cylindrical specimens.

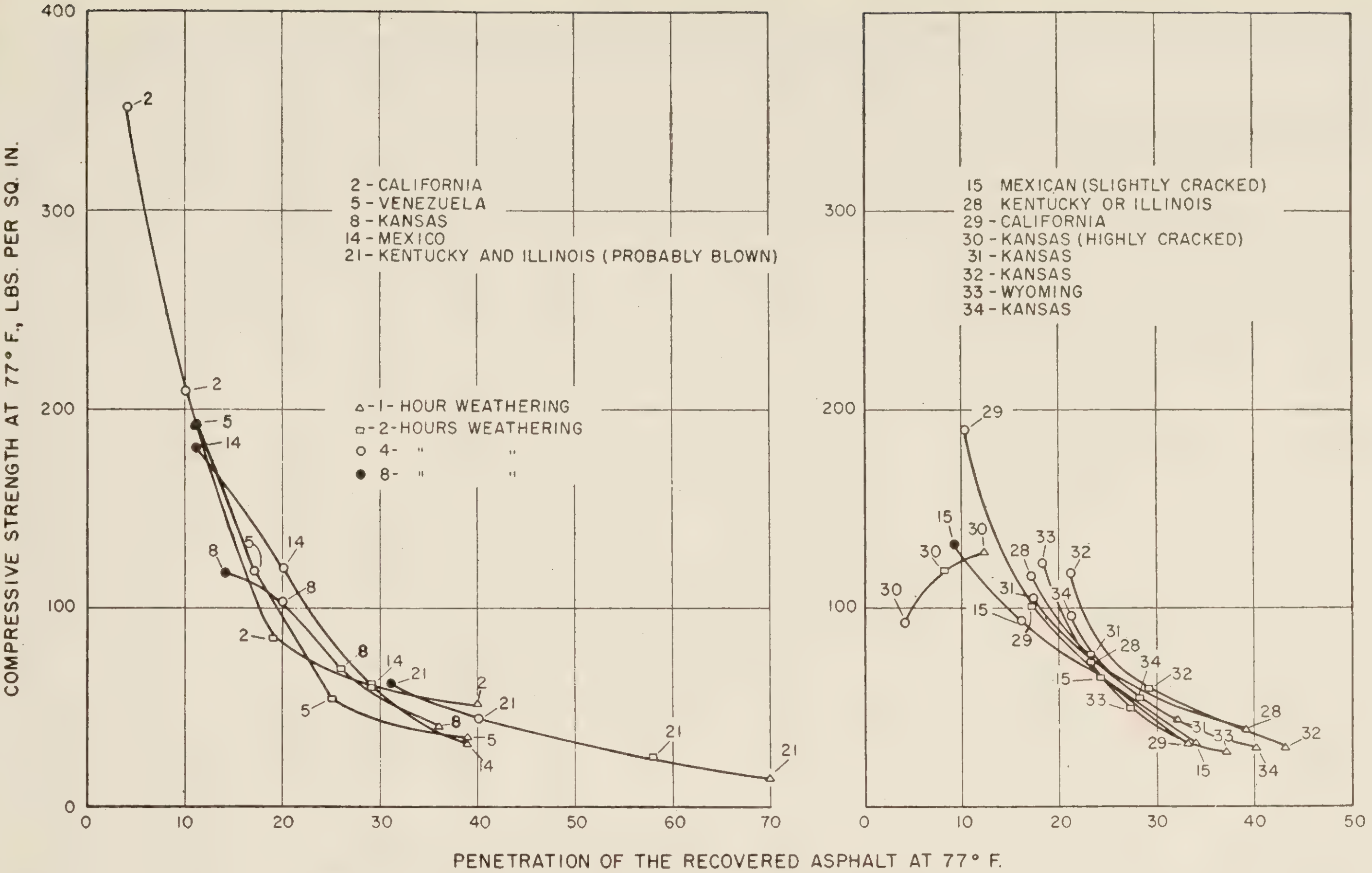


Figure 8.—Weathering-compressive strength test results. Relation between compressive strength and penetration of the recovered asphalt.

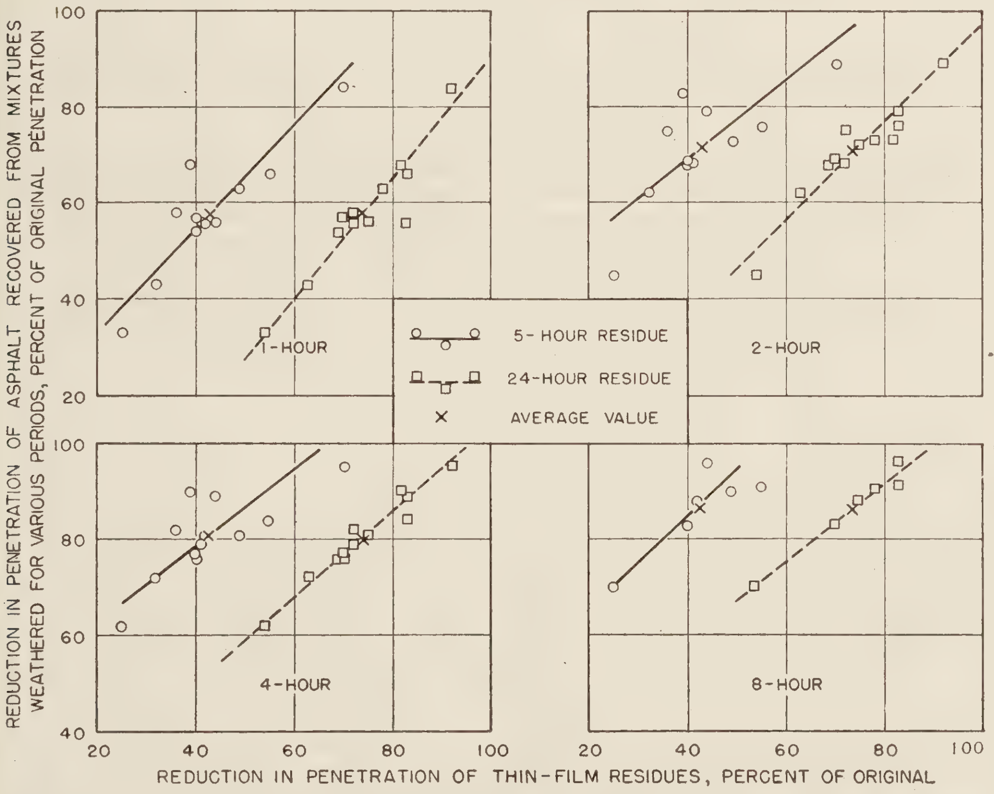


Figure 9.—Comparison of the reduction in penetration of thin-film residues with the reduction in penetration of asphalts recovered from oven-weathered mixtures.

On account of the differences in dimensions of the specimens, it is not to be expected that the amount of hardening that will occur in a given time in the weathering-strength specimens will be the same as that which occurs in the abrasion specimens. However, it is reasonable to assume that the rate of hardening will follow the same general trends in both types of test.

In figure 7 is shown, for typical materials, the relation between abrasion loss and the penetration of the asphalt recovered from the weathering-strength specimens. Table 7 shows that the hardness of the recovered asphalt—that is, the reduction in penetration and increase in softening point, increases with length of weathering. Both table 7 and figure 7 show that the abrasion loss increases as the penetration of the recovered asphalt decreases. The Kentucky and Illinois asphalt, No. 21, which had the least abrasion loss of all the materials tested, also showed the least hardening as evidenced by the penetration and softening point of the recovered asphalt. Other materials, such as Kansas No. 8, Venezuelan No. 5, and Mexican No. 14, which had low abrasion losses, also showed low rates of hardening up to 8 hours of weathering. In the case of the highly cracked asphalt No. 30, the asphalt hardened rapidly and had very high losses in the abrasion test.

It is evident that the abrasion loss is related to the consistency of the contained asphalt and that either may be used to determine the relative resistance of asphaltic materials to hardening.

Effect of Consistency

Figure 8 shows the compressive strength of the weathered specimens plotted against

Table 8.—Results of thin-film oven tests on asphalt cements

Identification and source of asphalt	Tests on original asphalt			Tests on residue from thin-film test, $\frac{1}{8}$-inch film exposed at 325° F.							
				5-hour test				24-hour test			
	Penetration at 77° F.	Softening point	Ductility at 77° F.	Penetration at 77° F.	Retained penetration [1]	Softening point	Ductility at 77° F.	Penetration at 77° F.	Retained penetration [1]	Softening point	Ductility at 77° F.
		° F.	*Cm.*		*Percent*	*° F.*	*Cm.*		*Percent*	*° F.*	*Cm.*
1. California	54	119	250+	33	61	128	250+				
2. Do	90	112	200	51	56	121	215	16	17	147	134
3. Do	131	107	150	68	52	118	200				
4. Venezuela	51	130	230	33	65	143	63				
5. Do	88	118	250+	51	58	132	242	22	25	171	5
6. Do	138	110	152	74	54	123	207				
7. Kansas	61	129	130	40	65	146	12				
8. Do	83	121	200	50	60	138	25	25	30	183	3
9. Do	137	110	154	73	53	127	105				
10. Do	92	115	115	60	65	141	10				
11. Kentucky	87	113	250+	28	28	139	24				
12. Do	102	111	170	28	27	142	15				
13. Wyoming	95	115	180	50	52	135	76				
14. Mexican	106	117	199	54	51	136	113	24	22	174	6
15. Do	101	118	106	46	45	143	12	18	17	219	3
16. Columbia	110	112	151	66	60	124	210				
17. Venezuela	97	117	165	50	51	140	28				
18. Do	105	114	140	62	60	128	140				
19. Arkansas	96	113	142	63	65	126	234				
20. Do	98	121	170	61	63	135	58				
21. Kentucky and Illinois	105	119	120	79	75	127	67	48	46	148	10
22. Trinidad	100	112	247	47	47	126	45				
23. Bermudez	102	112	58	33	27	126	28				
24. California	89	111	150+	47	52	136	230				
25. Field sample, Rhode Island	65	120	250+	40	61	134	250+				
26. Field sample, Virginia	89	114	214	60	67	127	237+				
27. Venezuela	64	125	220	40	62	141	90				
28. Kentucky or Illinois	93	116	154	60	64	127	235	26	28	157	8
29. California	102	111	203	62	61	119	250+	18	18	149	45
30. Kansas	75	115	158	22	30	137	47	6	8	191	0
31. Do	75	123	198	45	60	141	18	23	30	187	3
32. Do	76	122	142	52	68	133	121	28	37	166	5
33. Wyoming	85	119	186	50	59	132	170	24	28	165	5
34. Kansas	87	119	170	52	60	133	100	27	31	170	4
35. Kentucky or Illinois	89	122	188	63	71	132	127				
41. Venezuela	67	118	235	54	61	130	135				
42. Kansas	68	124	193	42	62	143	21				
43. Do	90	117	183	55	61	131	76				
44. Do	132	113	180	70	53	127	74				
45. Ohio	94	120	195	56	60	134	52				
46. Venezuela	54	129	250+	34	63	137	112				
47. Kentucky	89	118	187	54	61	128	195				

[1] Percent of original penetration.

the penetration of the contained asphalt after various periods of exposure. It is of interest to note that, in general, the points for most of the asphalts are close to one curve, indicating that the compressive strength varies inversely as the penetration of the contained asphalt. An exception to this is the highly cracked asphalt No. 30. At the end of 1 hour of weathering the penetration of this asphalt had been reduced to 12 from an original value of 75 and further weathering reduced both the penetration and strength. The highly cracked asphalts, No. 11 and No. 12, were not recovered from the weathered mixtures but it is probable that for these materials the trend of the relation between retained penetration and strength would be similar to that for asphalt No. 30.

The slightly cracked asphalt, No. 15, gave increased strength as the penetration decreased, although the rate of increase was slightly lower than for the uncracked materials. Of the uncracked materials, California asphalt No. 2 had the lowest penetration and the highest strength after 8 hours exposure, these being 4 and 352, respectively. Asphalt No. 30, a highly cracked asphalt, had a penetration of 4 after 4 hours exposure but had a strength of only 92 pounds per square inch. This would indicate that the highly cracked materials become brittle or fragile and lose their cohesive properties to a greater extent than do the uncracked materials.

Table 9.—Comparison of the penetrations of asphalts after the thin-film oven test with the penetrations of the same asphalts recovered from mixtures after weathering

Identification and source of asphalt	Oliensis spot test	Penetration at 77° F.			
		Original asphalt	Residue from thin-film oven test [1]	Recovered asphalt 1-year outdoor weathering	Recovered asphalt 22-hours ultra-violet light at 180° F.
A. Mexican	Negative	87	24	31	24
B. Midcontinent	Positive	98	8	15	11
C. Mexican	Negative	86	23	29	25
D. Midcontinent	do	90	30	35	32
E. Do	Slightly positive	85	25	33	29
F. Arkansas	Positive	81	15	19	22
G. Do	Negative	90	31	36	36
H. Texas	Slightly positive	87	19	20	21
J. Do	Negative	86	21	23	24
K. Mexican	do	80	23	29	24
N. Illinois	do	95	40	51	52
O. Arkansas	do	91	28	32	35
P. California	do	87	14	20	21
Q. Wyoming	do	90	17	28	28
R. Do	Slightly positive	91	17	30	29
S. California	Negative	93	12	23	16
T. Wyoming	do	83	13	21	18
U. Do	Positive	82	5	10	8
V. Kansas	Negative	92	24	28	30
W. Do	Positive	86	14	20	19
X. Kentucky	do	86	8	16	12

[1] $\frac{1}{8}$-inch film exposed at 325° F. for 25 hours.

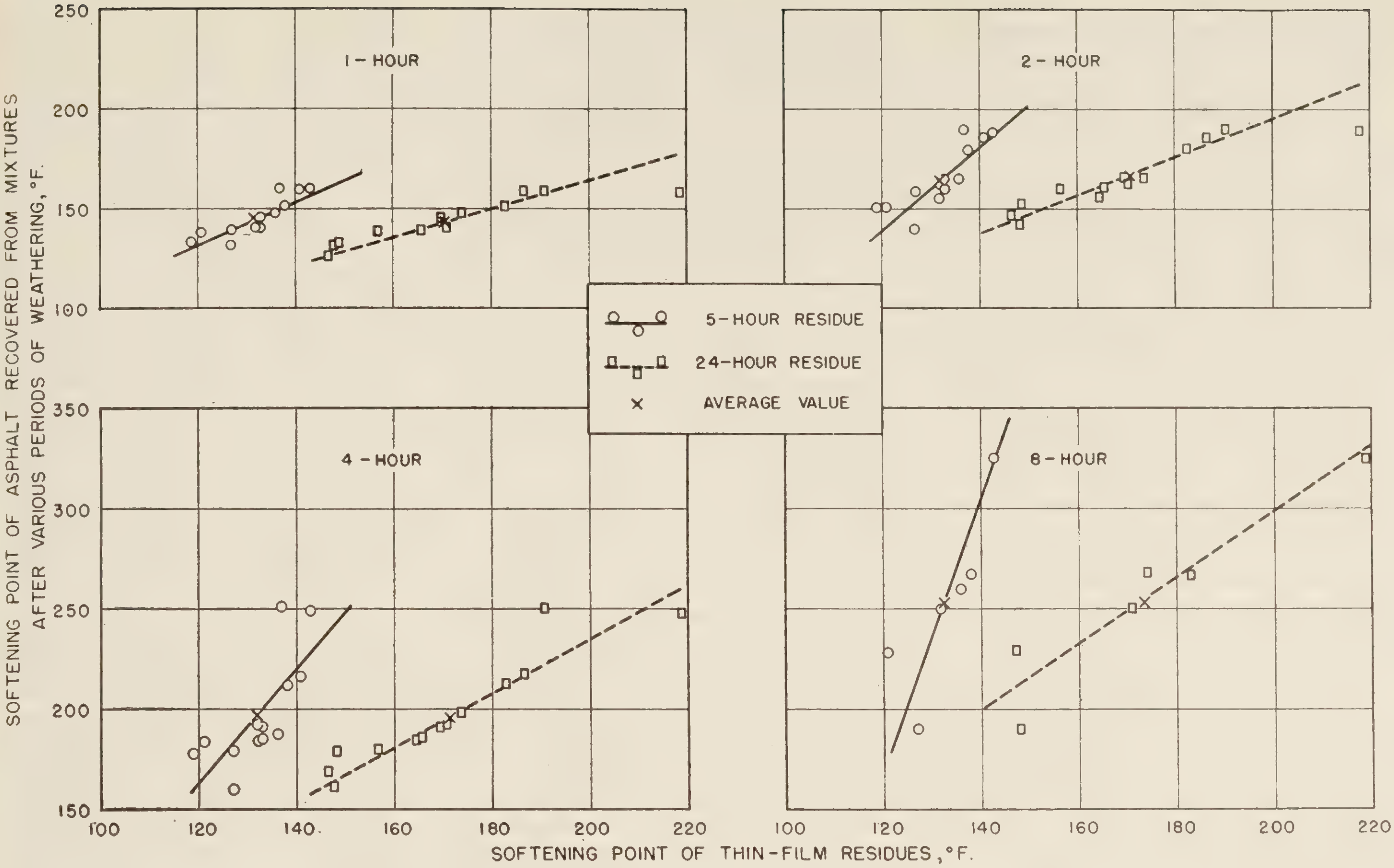


Figure 10.—Comparison of softening point of thin-film residues with the softening point of asphalts recovered from oven-weathered mixtures.

There is a wide difference in the amount and rate of hardening of the various asphalts included in this study. Some of the midcontinent asphalts had higher resistance to hardening than did some of the asphalts from the higher asphaltic-base crudes. The retained percentages of original penetration after 1 and 8 hours of weathering were 44 and 4, respectively, for California No. 2, 44 and 12 for Venezuela No. 5, 43 and 17 for Kansas No. 8, 37 and 10 for Mexican No. 14, and 67 and 29 for Kentucky and Illinois No. 21.

After weathering 1 and 4 hours, the percentage of original penetration retained by some of the other asphalts were as follows: For Kansas No. 30, a highly cracked material, 16 and 5, respectively; for uncracked Kansas material No. 32, 57 and 28, respectively; and for Mexican No. 15, slightly cracked, 34 and 16.

The results of a previous study[4] show that the physical properties of a given mix-

---

[4] *The effect of characteristics of asphalts on physical properties of bituminous mixtures,* by R. H. Lewis and J. Y. Welborn. PUBLIC ROADS, vol. 25, No. 5, Sept. 1948.

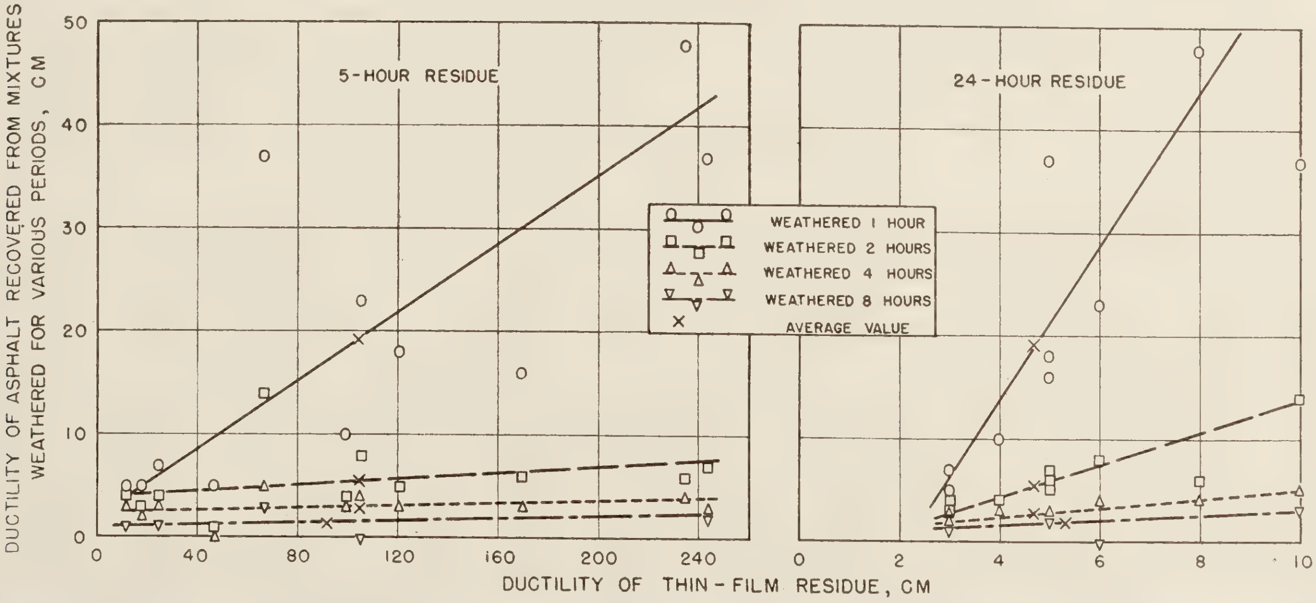


Figure 11.—Comparison of ductility of thin-film residues with the ductility of the asphalts recovered from oven-weathered mixtures.

ture are dependent upon the consistency of the contained asphalt at the test temperature. The results of the present work substantiates these earlier findings.

The results of the tests on the recovered asphalts from the test cylinders after weathering are summarized as follows:

1. There is a wide difference in the resistance of asphalts to hardening depending on the source of the crude petroleum from which the asphalt is obtained and the method of refining.
2. In general, the abrasion loss is dependent upon the consistency of the contained asphalt.
3. For the uncracked asphalts and those only slightly cracked, the compressive strength of the mixtures varied inversely as the penetration of the contained asphalt without regard to the source of the asphalts.
4. For the highly cracked asphalts, the relation between the compressive strength and the hardness of the contained asphalt is different than for the uncracked asphalts.

Behavior Dependent on Hardening

The foregoing studies of the abrasion and weathering-strength tests clearly show that the behavior of asphaltic materials in these tests is dependent largely upon the rate and amount of hardening that occurs during the exposure of Ottawa sand and asphalt mixtures to heat and air. Since both tests are time-consuming and require the control of many variables involved in their test procedures, they are not well suited for use as specification tests. Previous studies of the hardening properties of asphaltic materials have shown that the thin-film oven test also can be used to show the rate of change in asphaltic materials when subjected to heat and air. Therefore, a study has been made to determine the correlation that may exist between the results of this test and the results of the abrasion and weathering-strength tests.

Thin-Film Oven Tests

Thin-film oven tests were made on most of the asphalts used in this study in order to compare the characteristics of the residues obtained by this method of direct exposure of the asphalts to the characteristics of the asphalts after exposure in mixtures. The results of the thin-film oven tests are given in table 8, together with the test results on the original asphalts. In most of the previous work, the thin-film oven test has been made on a 50-milliliter sample of asphalt in an aluminum pan 5.5 inches in diameter, the film being exposed in an oven for 5 hours at 325°F. The same control is used as for the standard test for loss on heating. In order to produce greater changes in the asphalts by the thin-film oven test, which would be more comparable to the changes occurring during weathering of the mixtures, some of the asphalts used in this study were also exposed in the thin-film oven test for 24 hours. A detailed description of the method used for the thin-film oven test is given on page 202.

Comparisons of the reduction in penetration of the 5-hour and the 24-hour thin-film residues with the reduction in penetration of the asphalts recovered from the Ottawa sand and asphalt mixtures weathered for 1, 2, 4, and 8 hours are shown in figure 9, which presents the reduction in penetration as a percentage of the original penetration by the two methods of exposure. There is some dispersion of the points from the average curves for the 5-hour thin-film residues which may be accounted for by the wide difference in the severity of the two methods of weathering. The points for the 1-hour weathering period fall fairly close to the straight line, indicating that the amount of hardening produced by the two methods of exposure are in the same order. The comparision for the 24-hour thin-film residues in general is better than for the 5-hour thin-film test. It is of interest to note that the percentage reduction in the penetration of the asphalt from the 24-hour thin-film oven test is almost identical with the percentage reduction in penetration of the asphalt recovered from the mixture after weathering for 2 hours. It is apparent from the above comparisons that both methods of exposure give comparable results as to the hardening properties of asphalts.

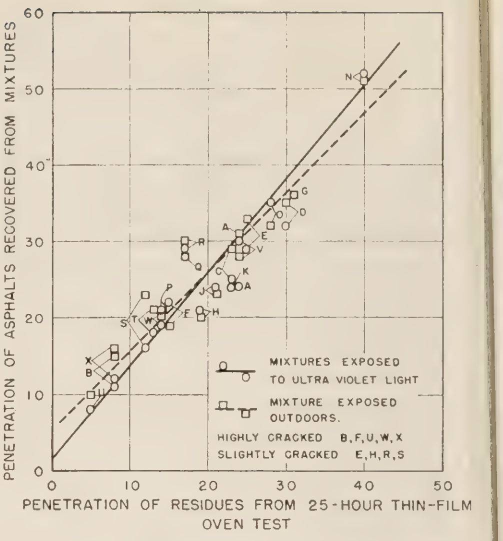


Figure 12.—Comparison of penetration of asphalt recovered from mixtures exposed to ultraviolet light and outdoors with the penetration of the thin-film oven test.

Comparisons of the softening points of the residues after the 5-hour and the 24-hour thin-film oven tests with those of the asphalts recovered from the weathered mixtures are shown in figure 10. As for the penetration data, this figure shows that changes in the asphalts as measured by the softening point, in general, are in the same order for the two methods of exposure. Here also the softening points of the residues from the 24-hour thin-film oven test are approximately the same as for the same

Table 10.—Comparison of the residues from the thin-film oven test with the recovered asphalts from the Shattuck mixing test

Identification and source of asphalt	Penetration of original asphalt at at 77° F.	Residue from thin-film oven test[1]				Recovered asphalt from Shattuck mixing test			
		Penetration at 77° F.	Retained penetration[2]	Softening point	Ductility at 77° F.	Penetration at 77° F.	Retained penetration[2]	Softening point	Ductility at 77° F.
RESULTS OF FIRST SERIES[3]									
			percent	° *F.*	*Cm.*		*percent*	° *F.*	*Cm.*
3. California	54	34	63	129	250+	25	46	135	250+
4. West Texas	52	37	71	138	77	36	71	138	66
6. Columbia	56	35	63	141	105	30	54	145	21
6A. Venezuela	54	35	65	141	145	27	50	150	20
8. East Texas	51	33	65	154	15	34	67	151	17
10A. Venezuela	58	33	57	146	62	22	38	158	7
12. Unknown	51	36	71	150	10	34	67	153	7
12B. Do	51	34	67	128	250+	29	57	130	222
RESULTS OF SECOND SERIES									
1. West Texas	55	43	78	135	158	40	73	135	60
2. Unknown	50	38	76	137	121	34	68	140	44
3. Do	53	37	70	133	244	38	72	134	148
4. West Texas	91	67	74	122	176	69	76	120	181
5. Do	90	62	69	124	250+	63	70	123	185
6. Venezuela	55	37	67	133	218	35	64	138	204
7. Do	84	53	59	129	168	44	49	135	102
8. California	57	37	65	125	250+	37	65	126	250+
9. Do	90	54	60	120	250+	47	52	122	250+

[1] ⅛-inch film exposed at 325° F. for 5 hours.

[2] Percent of original penetration.

[3] Reported in PUBLIC ROADS, vol. 22, No. 2, April 1941.

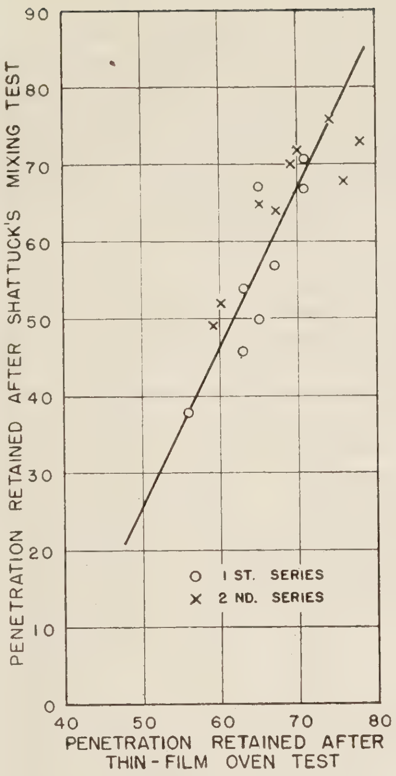


Figure 13.—Comparison of the penetration retained after the thin-film oven test and the Shattuck mixing test.

asphalts recovered from the mixtures weathered for 2 hours.

Figure 11 compares the ductility of the 5-hour and 24-hour thin-film residues with the ductility of the asphalts recovered from the weathered mixtures. Because of the inherent high ductility of the California asphalts, Nos. 2 and 29, and their abnormally large change in ductility with a small change in penetration, their values were omitted. With the exception of those asphalts, figure 11 shows a similarity in changes in ductility resulting from the two methods of exposure.

The above comparisons of penetration, softening point, and ductility of the asphalts recovered from the oven-weathered mixtures and those obtained from the thin-film oven test, show that the heating of asphalts in relatively thin film, as in the thin-film oven test, produces changes in their characteristics similar to those produced by exposing asphaltic mixtures to the same temperature.

Comparison with Other Tests

Lang and Thomas[5] studied the hardening properties of asphalt cements of the 85-100 penetration grade by exposing mixtures of Ottawa sand and these asphalts to the action of ultraviolet light and heat and to natural outdoor weathering.

In the exposure to ultraviolet light, the procedure was as follows: 3,000 grams of prepared Ottawa sand and asphalt mixture were placed in a twin pug-mill mixer which rotated at a speed of 160 r.p.m. for 22 hours. During this time the mixture was exposed to ultraviolet light from a mercury arc in quartz. The temperature of the mixture was maintained at 180°F. during the exposure period.

For the outdoor weathering, similar mixtures were exposed for a period of 1 year. At the completion of the exposure periods the asphalts were extracted and recovered from the weathered mixtures by the Abson method.

Lang and Thomas reported the results of thin-film oven tests made by the method which has just been described with a time of exposure of 25 hours. The results of the tests on the asphalts recovered from the mixtures exposed to ultraviolet light and outdoors and the results of the 25-hour thin-film oven test are given in table 9.

Comparison between the penetration of the thin-film residues and the penetration of the asphalts recovered from mixtures after exposure to ultraviolet light and after weathering outdoors is shown in figure 12.

The thin-film test for 25 hours exposure is shown, in general, to be somewhat more severe than either of the two methods of weathering used on the mixtures. All three test procedures show similar differences in the hardening properties of asphalts as influenced by the source of the material and whether or not, or to what degree, they have been cracked in the refining processes. The authors concluded from these studies that the hardening produced by natural weathering is very similar to that produced by artificial heat, air, and ultraviolet light exposure.

Another type of test for determining the relative resistance of asphalts to hardening is the Shattuck mixing test.[6] In this test, 1,880 grams of heated Ottawa sand are mixed with 120 grams of the asphalt to be tested for 1 minute in a laboratory pug-mill mixer under standard conditions of temperature. After mixing, the mixture is spread evenly in a shallow pan which is then placed in an oven at 350°F. for 30 minutes. The mixture is then removed and allowed to cool to room temperature. After cooling, the asphalt is extracted (using benzol) and recovered by the Abson method. The recovered asphalt is then tested for penetration, ductility, and softening point.

In a previous investigation[7] a study was made of the Shattuck test and it was found that the alterations in the asphalt which take place in this test are very similar to those that take place in the 5-hour, thin-film oven test. The results of a more recent study are shown in table 10, in which results obtained with the Shattuck mixing test and the 5-hour, thin-film oven test are compared. It may be noted in figure 13 that the two methods of test gave similar results.

---

[5] *Laboratory studies of asphalt cements,* by Fred C. Lang and T. W. Thomas. University of Minnesota Engineering Experiment Station Bulletin No. 15, Nov. 1939.

[6] *Measurement of the resistance of oil asphalts (50-60 pen.) to changes in penetration and ductility at plant mixing temperatures,* by C. L. Shattuck. Proceedings of The Association of Asphalt Paving Technologists, Vol. 11, 1940.

[7] First reference, footnote 1, p. 188.

ABRASION TEST PROCEDURE

Preparing the mixture

Standard Ottawa sand (No. 20–No. 30), as specified in standard method of test for tensile strength of hydraulic-cement mortars, A.S.T.M. Designation C 190, is used. In testing penetration grade asphalts, the sand is heated to 325°F. in an oven before mixing, while for tests on liquid asphaltic materials the sand is dried but not heated. Sufficient asphaltic material for each batch is heated to the application temperature while being stirred to prevent local overheating. The asphaltic material and Ottawa sand are combined in the proportion of 2 parts of asphaltic material to 100 parts by weight of sand.

Application temperatures used for the various asphaltic materials are:

Penetration grades	325°F.
Rapid-curing (RC), medium curing (MC), and slow-curing (SC) liquid asphaltic materials	200°F.
Emulsion	125°F.

Each test mixture is prepared in a batch of sufficient size to produce 15 test specimens. In testing asphalt cement the batch, after mixing, is spread out in shallow pans to a depth of about one-half inch and allowed to cool to air temperature. The mixer and the cooling pans are shown in figure 14. After cooling, 30 grams of the mixture is placed in each of fifteen 2⅜-inch ointment tins, each of which is numbered serially. These tins are then placed in an oven at 325°F. to warm the mix for molding.

The tins, each with its 30 grams of mixture, are placed in the oven one at a time at 3-minute intervals. Molding is started after 9 minutes and continued at the rate of one specimen each 3 minutes so that the pre-heating time for each 30-gram lot is uniformly 9 minutes.

In testing liquid asphaltic materials, the procedure is modified by a preliminary curing of the loose mixture in the large shallow pans in an oven at 140°F. for 18 hours. The

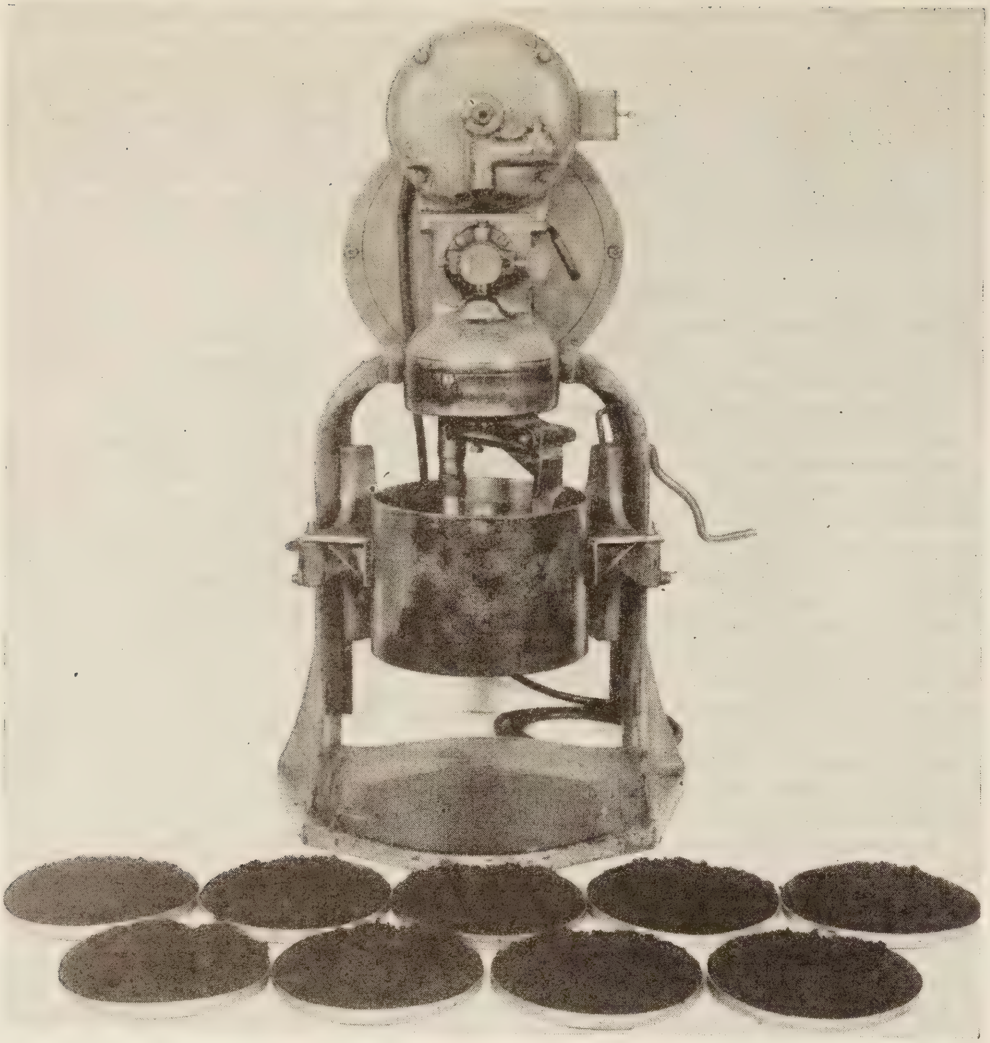


Figure 14.—Mixer and cooling pans.

subsequent cooling to air temperature, and the operations of weighing, heating, and molding are then carried out as described for the asphalt cements.

Molding and weathering

The test specimens are formed and tested in steel specimen cups having an inside diameter of 2 inches and a depth of ⅜ inch. A steel guide sleeve is provided to fit over the specimen cup during molding to retain the loose mixture and to center the compression plunger. Both the cup and the guide sleeve are warmed for 3 minutes in the 325°F. oven prior to being used in molding each test specimen.

The batch of exactly 30 grams of mixture, preheated for 9 minutes at 325°F., is quickly placed into the warm mold and compressed under a load of 1,000 pounds per square inch maintained for 1 minute. The actual molding temperature of the mixture will be approximately 300°F. if this procedure is followed carefully. After molding, the specimens contained in their steel cups are permitted to cool to approximately 77°F. prior to being weathered in the oven. Figure 15 shows the special equipment for molding.

Weathering periods of ¼, 1, 2, 4, and 8 hours are used. Three molded specimens are tested for each weathering period. Thus, 15 specimens are required for the full test. These are placed in an 18-inch square oven pan 3 inches in depth, covered with a 1/16-inch mesh screen, and exposed in an oven at 325°F. The pan and screen eliminate variable air draft and thus provide more uniform curing conditions for the specimens. After oven curing or weathering for the desired period at 325°F., and cooling to room temperature, the specimens together with the supporting cups are weighed and the weight is recorded. The specimens are then placed in the 77°F. air bath preparatory to being tested for resistance to abrasion.

Abrasion machine

Four thousand grams of lead shot, passing the No. 10 and retained on the No. 14 sieve, are used for each test unless a smaller amount causes sufficient erosion of the test specimen to expose the bottom of the retaining cup.

Figure 16 is a schematic drawing of the abrasion machine used in this study. It conforms essentially to the California design. The critical dimensions are shown on the drawing. The rate of rotation of the test specimen is approximately 340 r.p.m. The lead shot is dropped at a rate of approximately 2,000 grams per minute. The temperature of the test is controlled by placing the machine in an air bath in which the temperature is maintained at 77°F. Accurate temperature control is very important. The shot is stored in the air bath between tests.

Expressing abrasion loss

The abrasion loss is normally reported on the basis of loss per 1,000 grams of shot after a total of 4,000 grams of shot have been dropped. However, the test should be stopped short of 4,000 grams of shot in the event that the abrasion has progressed through the specimen to expose the bottom of the cup. In such cases, the loss per 1,000 grams is computed on the basis of the amount of shot dropped. The loss is determined to hundredths of a gram. Figure 15 shows specimens at various stages of abrasion.

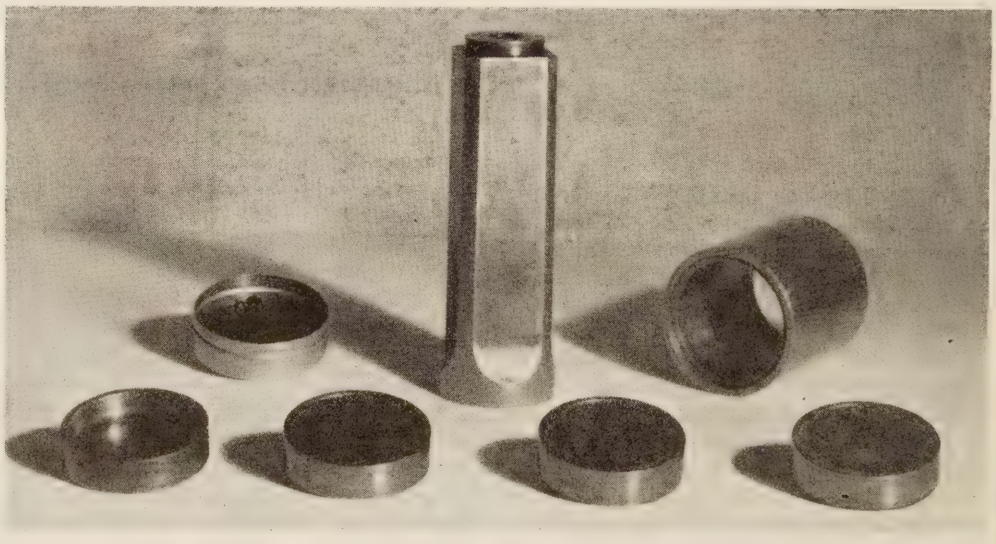


Figure 15.—In the background, special molding equipment. In the foreground, empty cup, freshly molded specimen, slightly abraded specimen, and highly abraded specimen.

WEATHERING-STRENGTH TEST PROCEDURE

Preparing the mixture

Two thousand grams of standard Ottawa sand (No. 20–No. 30) is required for each batch. Two batches are required for each set of 18 specimens. For asphalt-cement mixtures, the sand is heated to 325°F.; and for liquid asphaltic mixtures, the sand is at room temperature. Sufficient asphaltic material for each batch, while being heated to the mixing temperature, is stirred to prevent local overheating.

For mixing, the asphaltic materials are brought to the following temperatures:

Penetration grades (asphalt cement)	325°F.
RC or MC cutbacks	200°F.

Two thousand grams of sand and 80 grams, or 4 percent, of asphalt material are combined by mixing for about 2 minutes. The second batch to complete the full set of specimens is prepared in the same manner.

Curing the mixture

The prepared mixture, immediately after mixing, is spread to a uniform depth in pans 5.5 inches in diameter and ⅜ inch in depth, 200 grams of mix to each pan, and the pans set aside to cool to room temperature.

For the asphalt-cement mixtures, the pans containing the loose mix are then placed in the 325°F. oven for one-half hour. This is done at intervals of one every 5 minutes to allow time for molding. For the liquid asphaltic mixtures, a preliminary curing period of 18 hours in a 140°F. oven is used prior to the half-hour curing described above.

Molding test specimens

Molding follows immediately after the half-hour curing in the 325°F. oven. Molding is done by the double-plunger method with the molds preheated in a water bath to approximately 180°F. Enough of the 200 grams of mix (about 180 grams) from each pan is used to produce a cylinder 2 inches in diameter and 2 inches in height. It is important that the pans be removed from the oven in the same order in which they were put into the oven.

A molding pressure of 2,000 pounds per square inch is used and is held for 2 minutes. The temperature of the mix will be approximately 260°F. at the time of applying the molding load if the procedure is carefully followed.

After molding, the bottom plunger is removed, a base plate is inserted and the specimen pressed to the bottom of the mold

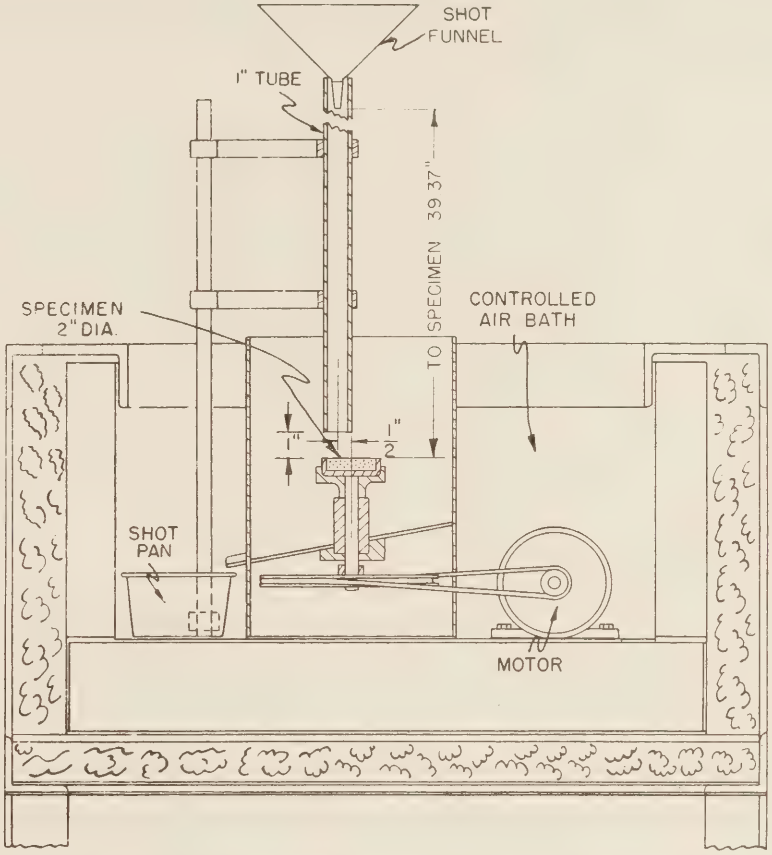


Figure 16.—Schematic drawing of abrasion machine.

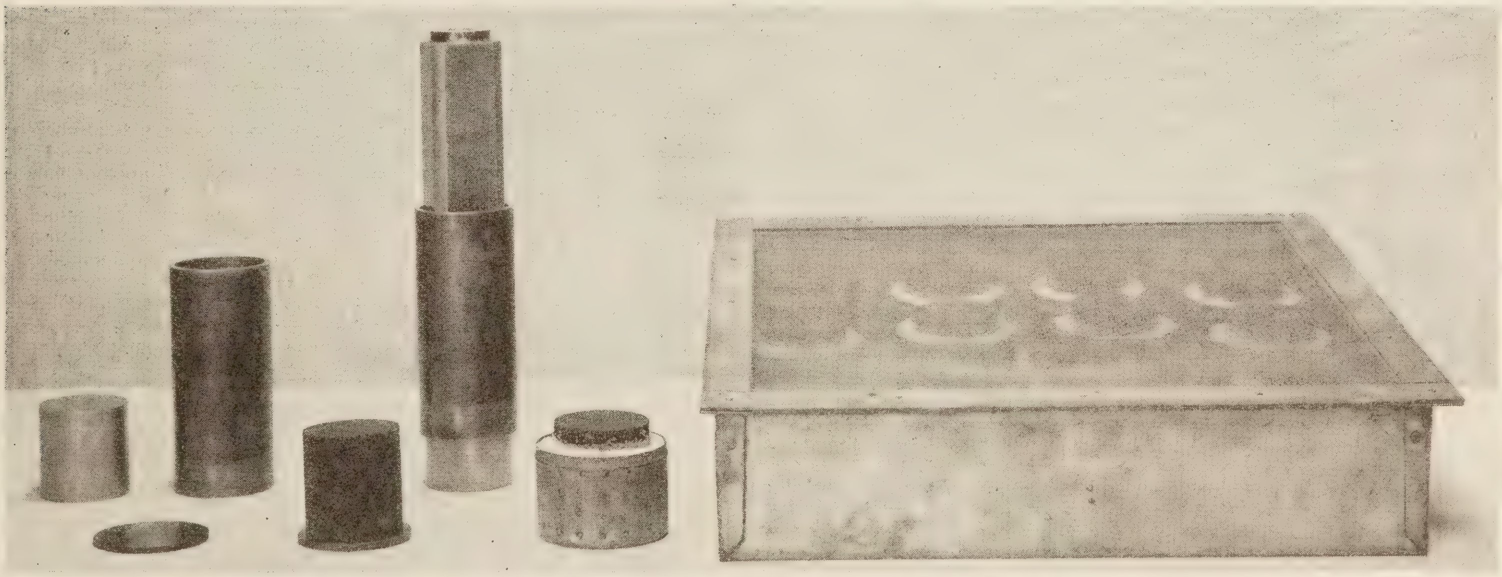


Figure 17.—Base plunger, base plate, centering and retaining sleeve, molded specimen, assembled mold, specimen supported by sand, and pan with screen cover used in oven weathering.

against the top of the plate. The molding cylinders containing the molded specimens are then placed in a 77°F. air bath for about 16 hours. After cooling, the specimens, with the base plates adhering, are pressed out of the mold and placed in specially prepared 6-ounce cans to undergo oven weathering.

The 6-ounce cans are perforated with sixty-four 1/16-inch holes on the side. As the specimens are placed in the perforated cans, Ottawa sand is filled in around the specimens in order to prevent their deforming during the period of heat-treatment in the oven.

Oven exposure

The cans containing the specimens and reinforced with No. 20–No. 30 Ottawa sand, as described above, are then placed in an oven pan about 18 inches square and 3 inches in depth, covered with a 1/16-inch mesh screen, and exposed in an oven at 325°F. The pan and screen eliminate variable air drafts and thus provide more uniform curing conditions for the specimens.

Three specimens are required for each oven-weathering period. Weathering periods of 1, 2, 3, 4, 6, and 8 hours have been used. Each set of three containers with their respective specimens are removed at the end of each oven-exposure period and placed in the 77°F. air bath prior to being tested in compression. Figure 17 shows the apparatus used in this test procedure.

Compressive strength

After cooling to 77°F., the specimens are removed from the cans, the base plates removed, and adhering Ottawa sand and particles brushed off. They are then tested in compression at a unit deformation rate of 0.1 inch per minute. The compressive strength and the deformation at the point of maximum strength are recorded.

THIN-FILM OVEN TEST PROCEDURE

Scope

The thin-film oven test is intended for the determination of the effect of heat and air on asphaltic materials when heated in thin films as hereinafter prescribed. The loss in weight, and a comparison of the penetration, softening point, and ductility before and after heating are used as a measure of the effect of this test on asphaltic materials. For additional information of the changes that occur in the asphaltic materials, solubility and Oliensis tests also may be used.

While this test is prescribed primarily for asphalt cements, it may also be useful for cutback asphalts. For the latter material, the test should be made on the residue from distillation obtained by the standard method of test for cutback asphaltic products, A.S.T.M. Designation D 402.

Preparing the mixture

Samples of the bituminous material, 50.0 ± 0.5 milliliters in volume, are weighed (weight calculated from specific gravity) into a tarred aluminum pan 5.5 inches in diameter and ⅜-inch deep, with a flat bottom. A 50-milliliter sample in this size container gives a film thickness of approximately one-eighth inch. Semisolid materials should be heated to a fluid condition previously. If the material has been heated to facilitate transfer, the container and sample should be cooled to room temperature. The weight should be determined to the nearest hundredth of a gram.

Oven exposure

An oven conforming to the oven specified in the tentative method of test for loss on heating of oil and asphaltic compounds, A.S.T.M. Designation D 6, is used, except that the circular shelf is constructed so that it will support one or more of the sample containers in a horizontal position.

With the oven at 325°F., the sample in its container is placed on the circular shelf in the oven and the shelf is rotated at a rate of 5 to 6 r.p.m., for 5 hours. At the conclusion of the heating period, the sample is removed from the oven, cooled to room temperature, and weighed to the nearest hundredth of a gram. The loss due to heating is then calculated.

Tests of residue

The residue from the thin-film oven test is melted at the lowest possible temperature, mixed thoroughly, and transferred to a 3- or 6-ounce container as used for the A.S.T.M. penetration test. In order to provide sufficient material for tests on the residue, it is often necessary to make the thin-film oven test in duplicate, in which case the residues are combined for testing. The thoroughly mixed residue is tested according to A.S.T.M. standard methods of test for penetration (Designation D 5), softening point (Designation D 36), and ductility (Designation D 113).

A list of the more important articles in
BLIC ROADS may be obtained upon request
dressed to Bureau of Public Roads, Washing-
25, D. C.

PUBLICATIONS
# of the Bureau of Public Roads

The following publications are sold by the Superintendent of Documents, Government Printing Office, Washington 25, D. C. Orders should be sent direct to the Superintendent of Documents. Prepayment is required.

ANNUAL REPORTS

Work of the Public Roads Administration:
1941, 15 cents. 1948, 20 cents.
1942, 10 cents. 1949, 25 cents.
Public Roads Administration Annual Reports:
1943; 1944; 1945. *(Free from Bureau of Public Roads)*
Annual Reports of the Bureau of Public Roads:
1950, 25 cents. 1951, 35 cents. 1952, 25 cents.

HOUSE DOCUMENT NO. 462

Part 1.—Nonuniformity of State Motor-Vehicle Traffic Laws. 15 cents.

Part 2.—Skilled Investigation at the Scene of the Accident Needed to Develop Causes. 10 cents.

Part 3.—Inadequacy of State Motor-Vehicle Accident Reporting. 10 cents.

Part 4.—Official Inspection of Vehicles. 10 cents.

Part 5.—Case Histories of Fatal Highway Accidents. 10 cents.

Part 6.—The Accident-Prone Driver. 10 cents.

UNIFORM VEHICLE CODE

Act I.—Uniform Motor-Vehicle Administration, Registration, Certificate of Title, and Antitheft Act. 15 cents.

Act II.—Uniform Motor-Vehicle Operators' and Chauffeurs' License Act. 15 cents. *(revised 1952)*

Act III.—Uniform Motor-Vehicle Civil Liability Act. 10 cents.

Act IV.—Uniform Motor-Vehicle Safety Responsibility Act. 15 cents. *(revised 1952)*

Act V.—Uniform Act Regulating Traffic on Highways. 20 cents. *(revised 1952)*

Model Traffic Ordinance. 20 cents. (*revised 1952*)

MAPS

State Transportation Map series (available for 39 States). Uniform sheets 26 by 36 inches, scale 1 inch equals 4 miles. Shows in colors Federal-aid and State highways with surface types, principal connecting roads, railroads, airports, waterways, National and State forests, parks, and other reservations. Prices and number of sheets for each State vary—see Superintendent of Documents price list 53.

United States System of Numbered Highways together with the Federal-Aid Highway System (also shows in color National forests, parks, and other reservations). 5 by 7 feet (in 2 sheets), scale 1 inch equals 37 miles. $1.25.

United States System of Numbered Highways. 28 by 42 inches, scale 1 inch equals 78 miles. 20 cents.

MISCELLANEOUS PUBLICATIONS

Bibliography of Highway Planning Reports. 30 cents.
Construction of Private Driveways (No. 272MP). 10 cents.
Electrical Equipment on Movable Bridges (No. 265T). 40 cents.
Factual Discussion of Motortruck Operation, Regulation, and Taxation. 30 cents.
Federal Legislation and Regulations Relating to Highway Construction. 40 cents.
Financing of Highways by Counties and Local Rural Governments, 1931–41. 45 cents.
Highway Accidents. 10 cents.
Highway Bond Calculations. 10 cents.
Highway Bridge Location (No. 1486D). 15 cents.
Highway Capacity Manual. 65 cents.
Highway Needs of the National Defense (House Document No. 249). 50 cents.
Highway Practice in the United States of America. 75 cents.
Highway Statistics (annual):
1945, 35 cents. 1948, 65 cents.
1946, 50 cents. 1949, 55 cents.
1947, 45 cents. 1951, 60 cents.
Highway Statistics, Summary to 1945. 40 cents.
Highways in the United States (*nontechnical*). 15 cents.
Highways of History. 25 cents.
Identification of Rock Types. 10 cents.
Interregional Highways (House Document No. 379). 75 cents.
Legal Aspects of Controlling Highway Access. 15 cents.
Local Rural Road Problem. 20 cents.
Manual on Uniform Traffic Control Devices for Streets and Highways. 75 cents.
Mathematical Theory of Vibration in Suspension Bridges. $1.25.
Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft, $2.00.
Public Control of Highway Access and Roadside Development. 35 cents.
Public Land Acquisition for Highway Purposes. 10 cents.
Roadside Improvement (No. 191MP). 10 cents.
Selected Bibliography on Highway Finance. 55 cents.
Specifications for Construction of Roads and Bridges in National Forests and National Parks (FP–41). $1.50.
Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces. 10 cents.
Transition Curves for Highways. $1.50.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

Bibliography on Automobile Parking in the United States.
Bibliography on Highway Lighting.
Bibliography on Highway Safety.
Bibliography on Land Acquisition for Public Roads.
Bibliography on Roadside Control.
Express Highways in the United States: a Bibliography.
Indexes to PUBLIC ROADS, volumes 17–19 and 23.
Title Sheets for PUBLIC ROADS, volumes 24, 25, and 26.

STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF JUNE 30, 1953

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$7,976	$23,520	$12,009	373.4	$8,104	$4,103	223.0	$34,674	$17,677	487.2	$66,298	$33,789	1,083.6
Arizona	803	5,520	3,864	119.1	1,906	1,337	13.8	6,088	4,027	88.0	13,514	9,228	220.9
Arkansas	7,552	8,344	4,493	256.9	4,253	2,144	185.8	14,589	7,422	287.0	27,186	14,059	729.7
California	3,647	14,481	6,667	101.9	20,747	10,272	60.3	101,775	50,758	283.1	137,003	67,697	445.3
Colorado	3,397	9,814	5,556	221.3	1,633	923	32.7	12,701	6,922	194.3	24,148	13,401	448.3
Connecticut	7,274	1,326	715	2.6	1,775	874	2.3	13,008	6,403	33.9	16,109	7,992	38.8
Delaware	2,820	1,668	836	8.4	55	28	--	7,120	3,602	31.9	8,843	4,466	40.3
Florida	4,565	21,435	11,048	329.7	5,860	3,018	124.3	15,038	7,587	216.4	42,333	21,653	670.4
Georgia	8,878	21,355	10,901	583.4	3,605	1,778	48.9	35,635	17,086	553.2	60,595	29,765	1,185.5
Idaho	3,011	12,111	7,356	312.6	3,543	2,212	72.8	10,245	6,523	189.5	25,899	16,091	574.9
Illinois	9,857	39,654	21,667	209.1	25,342	12,727	237.9	62,407	32,442	529.0	127,403	66,836	976.0
Indiana	10,525	37,435	19,549	170.1	11,165	5,520	87.0	27,677	14,882	189.2	76,277	39,951	446.3
Iowa	4,275	17,359	9,253	570.4	8,629	5,218	362.5	13,320	6,660	544.5	39,308	21,131	1,477.4
Kansas	5,526	11,810	5,829	956.4	9.330	4,557	488.5	14.413	6,969	642.6	35,553	17,355	2,087.5
Kentucky	4,332	14,122	7,338	194.8	7,283	4,019	96.7	19,931	10,046	306.8	41,336	21,403	598.3
Louisiana	4,108	16,713	8,385	124.1	8,869	4,424	58.4	23,005	11,017	121.3	48,587	23,826	303.8
Maine	1,163	9,996	5,003	86.3	442	231	.5	13,927	6,748	86.5	24,365	11,982	173.3
Maryland	7,954	10,005	5,176	79.8	2,952	1,338	26.4	8,647	4,779	38.9	21,604	11,293	145.1
Massachusetts	8,618	8,620	4,455	16.7	858	429	--	40,356	19,220	40.1	49,834	24,104	56.8
Michigan	8,163	29,418	15.248	585.6	7,991	4,027	188.6	55.558	24,105	237.1	92,967	43,380	1,011.3
Minnesota	4,875	12,078	6,611	943.6	10,769	5,600	784.6	16,491	8,943	484.8	39,338	21,154	2,213.0
Mississippi	2,083	17,106	8,617	584.6	5,085	2,523	235.9	20,481	10,537	556.6	42,672	21,677	1,377.1
Missouri	10,157	16,989	8,917	825.6	8,897	4,454	179.7	55,542	28,131	479.8	81,428	41,502	1,485.1
Montana	7,086	13,506	8,596	275.4	4,904	2,853	140.3	16,966	10,216	285.0	35,376	21,665	700.7
Nebraska	13,084	13,210	7,073	546.9	4,753	2,705	167.1	12,458	6,784	285.1	30,421	16,562	999.1
Nevada	5,166	4,260	3,565	73.8	883	739	35.6	6,261	4,875	178.2	11,404	9,179	287.6
New Hampshire	2,311	4,083	2,042	18.6	1,070	533	8.0	6,222	3,232	38.9	11,375	5,807	65.5
New Jersey	6,438	8,952	4,397	63.2	2,094	962	3.0	31,671	15,312	38.1	42,717	20,671	104.3
New Mexico	1,462	4,845	3,089	113.9	3,189	2,019	69.6	7,016	4,458	157.9	15,050	9,566	341.4
New York	24,133	91,698	48,018	199.9	40,597	20,531	147.1	126,376	58,545	345.9	258,671	127,094	692.9
North Carolina	6,740	22,781	11,033	453.2	4,570	2,232	189.6	32,026	15,425	597.0	59,377	28,690	1,239.8
North Dakota	2,445	5,344	2,686	953.1	7,888	3,944	699.9	9,028	4,691	656.5	22,260	11,321	2,309.5
Ohio	8,357	24,724	11,796	149.1	23,859	11,455	82.2	79,483	40,198	101.6	128,066	63,449	332.9
Oklahoma	11,917	8,332	4,605	186.7	6,002	3,162	92.8	16,309	8,571	239.8	30,643	16,338	519.3
Oregon	3,308	858	463	15.2	3,760	2,250	103.5	15,259	9,162	215.2	19,877	11,875	333.9
Pennsylvania	5,707	43,393	20,168	75.4	26,465	12,591	64.3	86,731	43,152	218.2	156,589	75,911	357.9
Rhode Island	2,008	3,277	1,638	31.9	161	80	--	19,316	10,037	28.9	22,754	11,755	60.8
South Carolina	5,936	7,881	4,371	178.4	2,704	1,331	142.2	19,478	10,026	377.9	30,063	15,728	698.5
South Dakota	1,363	9,938	5,902	678.6	4,225	2,410	240.7	8,198	4,940	392.1	22,361	13,252	1,311.4
Tennessee	4,301	16,733	9,254	537.4	7,657	3,672	209.3	35.338	15,780	283.0	59,728	28,706	1,029.7
Texas	17,144	4,714	2,380	103.1	18,940	10,756	380.9	57,060	31,068	900.1	80,714	44,204	1,384.1
Utah	490	3,536	2,698	52.4	2,758	2,088	57.3	12,706	9,594	174.9	19,000	14,380	284.6
Vermont	576	4,501	2,435	46.9	1,486	743	12.4	8,839	4,404	60.5	14,826	7,582	119.8
Virginia	2,153	16,102	6,901	171.8	9,655	4,561	142.2	33,278	16,380	268.8	59,035	27,842	582.8
Washington	2,538	9,633	4,954	193.5	4,606	2,536	91.1	14,522	7,689	109.7	28,761	15,179	394.3
West Virginia	5,289	6,847	3,454	43.2	3,960	2,004	6.2	19,700	9,863	157.4	30,507	15,321	206.8
Wisconsin	4,675	14,057	7.657	268.4	7,464	3,568	190.0	38,823	19,703	404.1	60,344	30,928	862.5
Wyoming	975	3,043	1,996	77.7	2,365	1,550	93.5	7,672	5,056	136.5	13,080	8,602	307.7
Hawaii	1,460	2,919	1,426	7.5	1,526	738	5.2	10,225	4,944	19.4	14,670	7,108	32.1
District of Columbia	1,176	7,808	3,664	6.0	4,837	2,214	2.0	11,148	5,282	1.9	23,793	11,160	9.9
Puerto Rico	3,673	11,496	5,322	57.3	1,174	572	4.8	13,899	6,633	44.7	26,569	12,527	106.8
TOTAL	283,470	729,350	381,076	13,234.9	362,645	186,555	6,891.4	1,378,636	698,506	13,339.0	2,470,631	1,266,137	33,465.3

U. S. GOVERNMENT PRINTING OFFICE 72196

UNITED STATES
GOVERNMENT PRINTING OFFICE
DIVISION OF PUBLIC DOCUMENTS
WASHINGTON 25, D. C.

OFFICIAL BUSINESS

PENALTY FOR PRIVATE USE TO AVOID
PAYMENT OF POSTAGE, $300
(GPO)

If you do not desire to continue receiving this publication, please CHECK HERE ☐ tear off this label and return it to the above address. Your name will then be promptly removed from the appropriate mailing list.